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Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

DEVELOPMENT AND VALIDATION OF AN AUTOMATED TEST BENCH FOR ELECTRONIC PRODUCTS

A Master's Thesis
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by

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Abstract

This master's thesis shows the development of a test bench for a flow sensor devices calibration. The project development will be carried out at a company, between February 2017 and July 2017. Therefore, during the project time, the test bench will be designed, developed and tested. The purpose of the test bench is the calibration for one of the products that the company is currently developing. For the product calibration, it is necessary air flowing into. For the current test bench, the calibration needs an operator to control air flow by using manual valves. However, the calibration process is long and if the operator is not on site, the calibration process may fail. So the new test bench will include three modes of operation, which will be explained for the next chapters.

Acknowledgements

First of all, my acknowledgments goes for Hector Ortiz, for giving me the chance to be involved in a real big project and for Miquel Ribalda, which his inestimable help was essential for the project.

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Revision history and approval record

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Table 1: Revision history and approval record

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CHAPTER 1 INTRODUCTION

The main purpose of the project is to make a new test bench for security devices calibration. The calibration is carried by air flowing into the device. This air flow must be controlled for the proper product calibration. Furthermore, the number of devices to calibrate at the same time is 4 as maximum. In order to know which is the air flowing through the system, two probes will be placed in the test bench in order to measure air flow.

1.1 Project Planning

1.1.1 Work packages

Project: Basic design	**WP ref: 1**	
Main component: Hardware	Sheet: 1 de 7	
Brief description: Understand what is needed and design a circuit to implement	Initial date: 01/03/2017 Final date: 14/03/2017	
Understand the project calibration	Delivery:	Date:
Design a circuit that fits the purposes	Circuit design	14/03/2017

Table 1.1: Basic design

Project: Prototype construction	**WP ref: 2**	
Main component: Hardware	Sheet: 2 of 7	
Brief description: Build a prototype based on the approved design	Initial date: 15/03/2017 Final date: 28/03/2017	
Since the circuit is composed by 8 equal parts, construct a prototype of one single part	Delivery:	Date:
	Prototype	28/03/2017

Table 1.2: Prototype construction

Project: Detailed design	**WP ref: 3**
Main component: Hardware	Sheet: 3 of 7
Brief description: Once the prototype is approved, design the whole circuit and order the remaining components	Initial date: 29/03/2017 Final date: 24/04/2017

Table 1.3: Detailed design

Project: Final unit construction	**WP ref: 4**	
Main component: Hardware	Sheet: 4 of 7	
Brief description: Start to construct the final unit when the components have arrived	Initial date: 26/04/2017 Final date: 14/03/2017	
Check all the components are available to start to build	Delivery:	Date:
Get a test bench to build on Start to mount	Final unit built	09/05/2017

Table 1.4: Final unit construction

Project: Testing and adjustment	**WP ref: 5**
Main component: Hardware	Sheet: 5 of 7
Brief description: When the final unit is finished, the start calibration and test the hardware and software together	Initial date: 10/05/2017 Final date: 11/06/2017
Check if hardware works for the purposes designed Check if software is adapted for the new test bench Test repeatable and reproducible and start to mount	

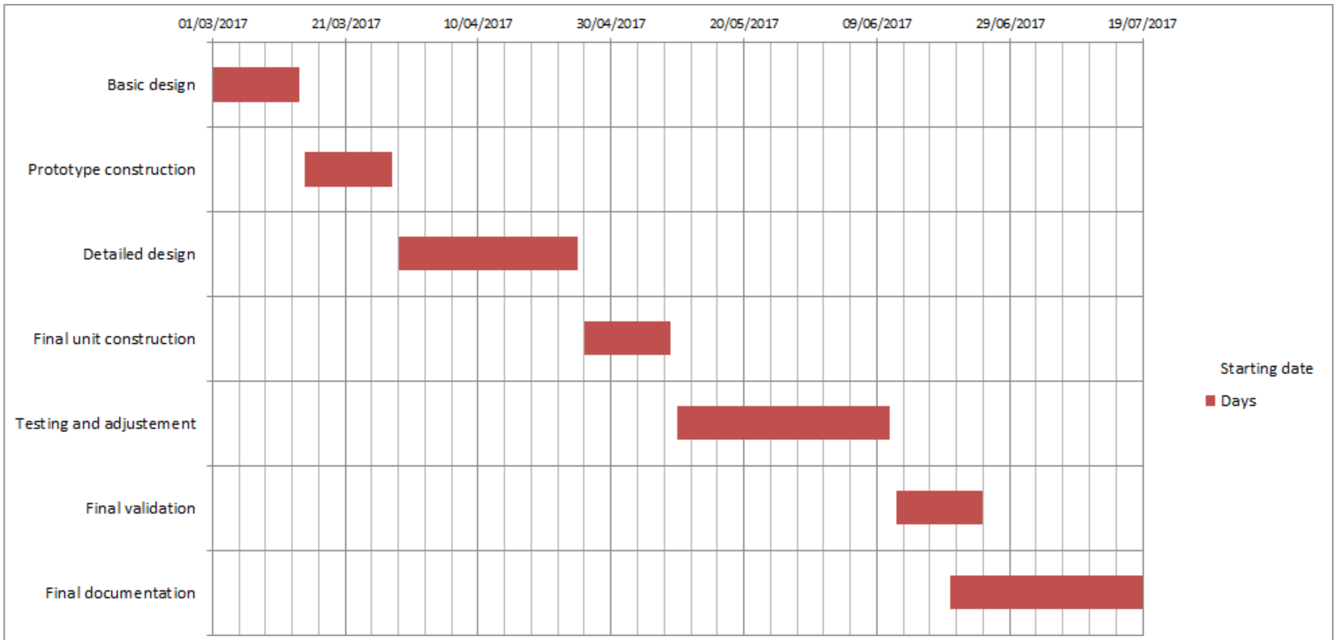
Table 1.5: Testing and adjustment

Project: Final validation	**WP ref: 6**
Main component: Hardware	Sheet: 6 of 7
Brief description: When checked the previous step, start to calibrate several devices	Initial date: 12/06/2017 Final date: 25/06/2017
Device calibration	

Table 1.6: Final validation

Project: Final documentation	**WP ref: 7**	
Main component: Hardware	Sheet: 7 of 7	
Brief description: Finish the project documentation and prepare presentation	Initial date: 20/06/2017 Final date: 20/07/2017	
Deliver final report	Delivery:	Date:
Present the project	Final report Final presentation	10/07/2017 20/07/2017

Table 1.7: Final documentation



	Final documentation	Final validation	Testing and adjustement	Final unit construction	Detailed design	Prototype construction	Basic design
Starting date	20/06/2017	12/06/2017	10/05/2017	26/04/2017	29/03/2017	15/03/2017	01/03/2017
Days	29	13	32	13	27	13	13

Figure 1.1: Gantt diagram

1.2 Requirements and specifications

One of the requirements is to create a product as modular as possible and ease of use for the operators. It means that the operator just have to connect all the modules properly and make them work in an easy way. Moreover, the way to avoid a failure in the modules connection is to be sure that all the connections possible only have one single way to be linked. In other words, many types of different connectors shall be used for this purpose.

It is desired to have three modes of operation for product calibration:

- Automatic/Software mode
- Manual mode
- 24 Voltage Direct Current (VDC) input mode

The automatic mode corresponds to control the air flow input via software. In fact, there is a software at the company which its task is to calibrate the device. However, the air flow must be controlled manually. Hence, the test bench must include this mode to avoid a compulsory human iteration for the whole time calibration.

The manual mode corresponds to control the air flow manually using switches. Right now, it has being used manual valves. This mode is included if software mode fails and/or for testing. So that, there is no limitation when it is going to be used.

Finally, the 24VDC input corresponds to control the air flow supplying the device with 24 VDC. This mode is included because, usually, the devices developed at the company are supplied by 24 VDC, so that it is a proper option to take into account in order to make a flexible test bench.

The way to control the air flow is by using electric valves. The valves behavior is very simple. They let pass air through or not depending on the electric signals that they receive. The specifications of the valve will be explained in valve section 2.4.

CHAPTER 2

STATE OF THE ART

2.1 Product

The product to be calibrated is a flow sensor based on the hot wire principle [1]. The principle explains that one part of the wire is heated by an external source, but not the remaining. So, when a fluid, in this case air flow, goes trough the wire and part of the wire gets cold and the remaining part gets colder. Therefore, the temperature difference between both points it may extracts the air flow driving through the hot wire. In this case, it has being used temperature sensors for this purpose, being one of them externally heated by a resistor.

2.2 Current test bench

At the company, it is developing security devices. Many of them, need air current flowing through for their proper behavior. However, this air flow must be controlled since the results provided may be wrong because of lack of control. So the device needs to know the air flowing through. Therefore, a calibration process is needed to provide this information.

The current calibration process is carried as follows. It is mainly composed by two parts, software and mechanical. On the software side, its main task is to establish a communication between the computer and the security device. This communication is necessary to proceed the calibration process. On the mechanical side, in order to control the air flowing through the device, manual valves and an anemometer have been used as it seen in figure 2.1.

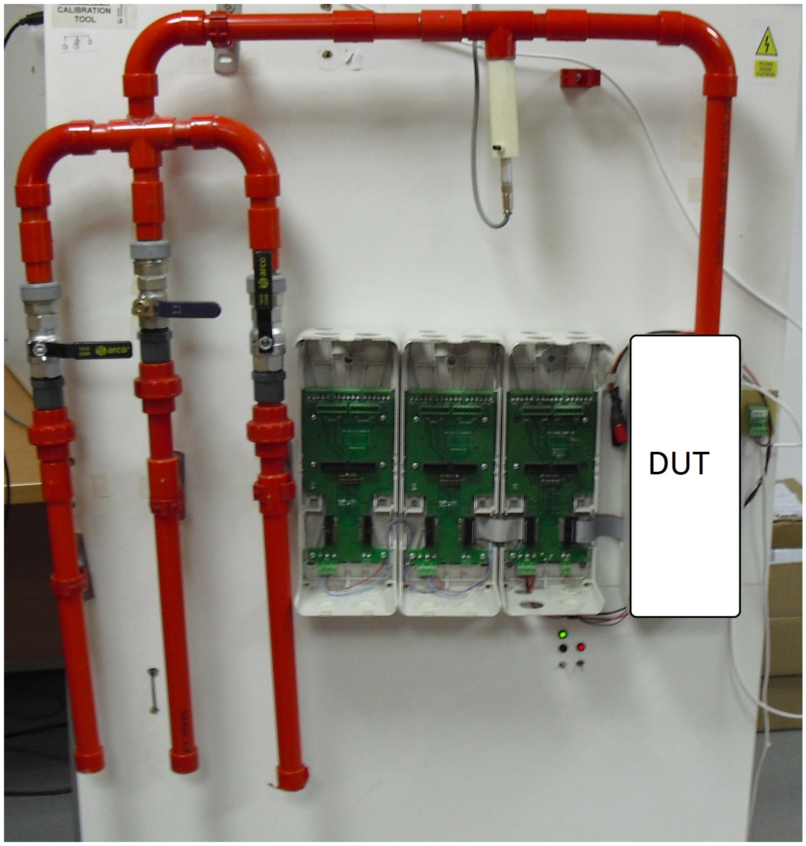


Figure 2.1: Current test bench using manual valves

There is a junction between software part and mechanical part, since the calibration cannot be done if there is no combination of both of them. The software indicates how the position of the valves has to be, is to say, open or close. Hence the operator, which its task is to control the valves, has to be awaiting when the software indicates there is a change in the valve position. A correct calibration process has a duration about 40 minutes. Moreover, every calibration time only it is calibrated one single device.

The main problem relies if the operator does not change the valves position when the software indicates it. If there is no change in valves position when the software indicates it, the calibration process get paused and calibration time is even larger. So human's fails are desired to be avoided, so that's why the project proposed will be developed.

Currently, the number of devices that can be calibrated within one calibration process is only one. So that, on calibration process with a duration of 40 minutes it has been calibrated one single device. The target of devices to be calibrated in one single day is 20 and it takes 13 hours and 20 minutes approximately. Although all the calibrations have carried out correctly, the time taken by an operator to calibrate (also called takt time) is very large. Therefore an automatic process is needed to reduce the takt time, which is one of the project requirements.

2.3 Calibration process

In this section, the calibration process will be explained in order to know how to develop the new test bench. As it is observed on the figure 2.1, there are three valves and they are joined in one single point. It means that air flow entering into the pipes (internal blower suck out the air), if the valve are open, then the air flows will be join in the junction and then they will be added. By this way it may control the air flowing into air flow detector. At the end of each pipe, it is placed an end cap with a hole, which its diameter determines the air flow entering to the pipe. So for a proper calibration, it is needed three known air flows, within a margin, driving into the device:

- 1 m/s, within a 0.7 m/s and 1.3 m/s span.
- 3 m/s, within a 2.4 m/s and 3.6 m/s span.
- 6 m/s, within a 5.1 m/s and 6.9 m/s span.

Air flows are measured by an external anemometer, which is connected to the calibration software. From this point on, the software will store the readings coming from the external anemometer, and at the end of the process, in order to know if the calibration process success, internal device calculations are made using the values stored from the anemometer. Once it is known how to get desired air flows and how to know if the calibration process success, the steps to follow to calibrate are the following:

- Step 1: An automatic process warms up the internal blower.
- Step 2: First calibration point, when 1 m/s shall enter into the air flow sensor for 20 minutes because of temperature stabilization.
- Step 3: Second calibration point, when 3 m/s shall enter into the air flow sensor for 5 minutes.
- Step 4: Third calibration point, when 6 m/s shall enter into the air flow sensor for 5 minutes.
- Step 5: Load into the detector the data stored from the external anemometer at three different calibration points.
- Step 6: Internal calculations verify a correct calibration process.
- Step 7: Save the calibration data process into a log file.

2.4 Valves

One of the specifications is to use a selected valve for this project. The valve model selected is the CP5C3 [2] from RS components and it needs to be activated by using 24 Voltage Alternating Current (VAC). The specifications are as follows:

- Power supply 24 VAC 50 Hertz (Hz)
- Power consumption 10 Watt (W)
- Operation time: 20 to 25 seconds
- Working temperature: -20°C to +80°C
- Micro-switches can pass up to 1 Ampere (A)
- Reversing motor
- 100,000 cycle life tests

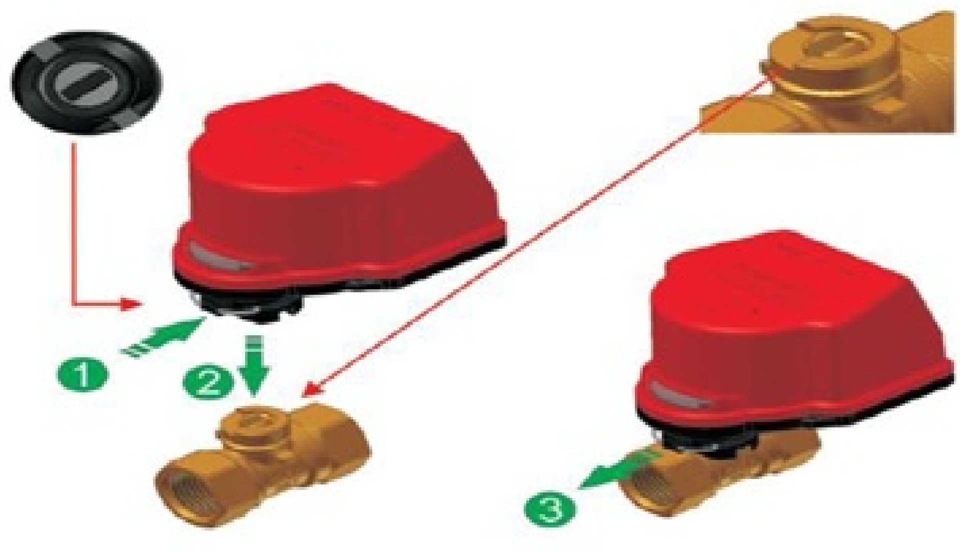


Figure 2.2: Valve

The model selected is the 3 wire control. This model has 6 wires, 4 dedicated to valve control and 2 (one shared with the control side) for feedback. On the control side, the four wires are the following according to their color:

- White: Neutral
- Green: Ground
- Black: Power for opening (Counterclockwise (CCW) rotation)
- Gray: Power to closing (Clockwise (CW) rotation)

To make them work is very simple. From the electric grid, neutral, ground and phase should be carried to the wires specified above. There must be a transformer between the grid and the valve in order to reduce 230 VAC to 24 VAC. So that, the ground may be directly connected from the grid to the valve and neutral and phase at the transformer output shall be connected to the remaining wires. The neutral coming from the transformer it is connected to the white wire and the phase shall be connected to the black wire if it is desired to open the valve or the gray one if it is desired to close the valve. These operations are demonstrated on the figure 2.3 and on the figure 2.4 for closing and open the valve respectively. One of the goals of the project is to control the valve opening and closing by ourselves.

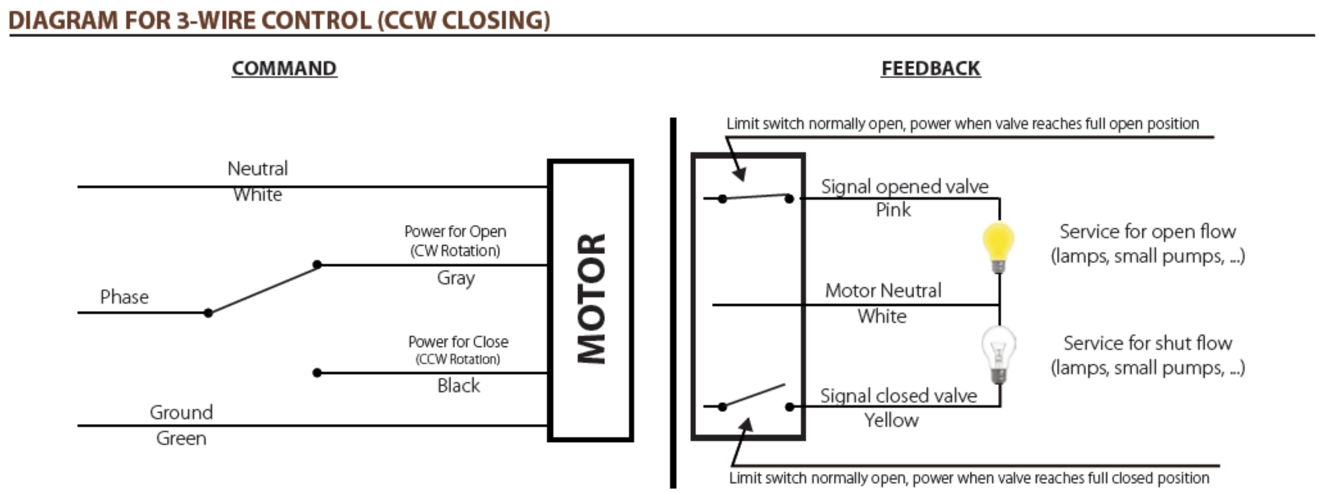


Figure 2.3: Close valve connections

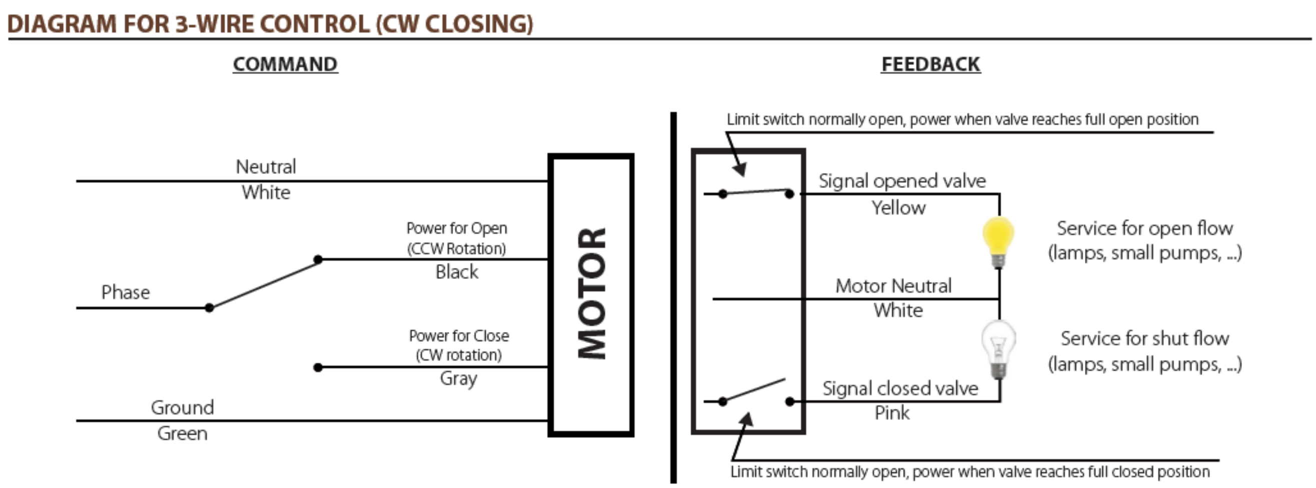


Figure 2.4: Open valve connections

On the feedback side, there are two physical wires, but it needs the neutral one to work properly. The wires are the following according to their color:

- Yellow: Signal opened valve
- Pink: Signal closed value

The behavior in this case is very simple. There is an AC signal between pink and white wires when the valve reaches open position or between yellow and white when the valve reaches closed position. So that, it can be connected a bulb for a visual feedback or design other method to get profit of this feedback already provided.

A proper way to make the valves open or close is by using relays, since the valve position may be switched by applying an electric signal according to the relays features, explained in the relay's section. So that, in the design stage, a driver shall be designed to control the relays by using electric signals.

2.5 Relay

As it has been explained in the valves section, relays are needed to let pass 24 VAC to the valve's phase in order to make them work. In the power supply box section will be explained how 24 VAC are achieved.

The relay has two positions, which it will take profit to switch from valve's open position to valve's close position by using one single electric signal.

The relay behavior [3] is as follows. It is composed by an inductor, two contacts and a conductor between to switch. In normal state, is to say, when there is no current in the inductor, one of the contacts is being touched by the conductor. However, when there is a current flowing through the inductor, it creates an electromagnetic field and it causes an attraction to the conductor, switching its position and touching the other contact. By this way, letting pass current through the inductor, it is may switch the position of the relay.

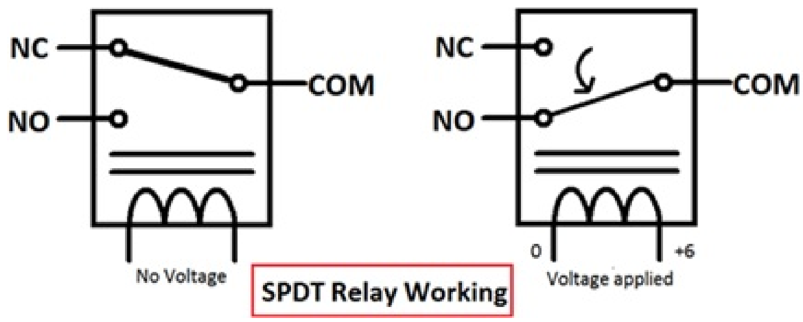


Figure 2.5: Schematic how a relay works

The relay has 5 ports:

- Normally Close (NC)
- Normally Open (NO)
- Common (COM)
- Coil positive port (Coil+)
- Coil negative port (Coil-)

When there is no current in the coil, the COM port is connected to NC. Otherwise, when there is current in the coil, COM port is connected to NO. The coil has two ports, one for higher voltage (Coil+) and other one for lower voltage (Coil-). The coil needs a certain voltage (and current) to work that always is indicated in the specifications.

The relay chosen for this project is 48.61.7.024.0050SPA, widely used in the company for testing. Its features are summarized below:

- It works at 24 VDC, standard value in the company.
- 35mm DIN rail slot included, very useful to order.
- It supports up to 16 A
- 20 millions life cycles
- Indicating led and flyback diode included

- Coil current consumption (minimum): 22.2 mA
- Simple Pole Double Throw (SPDT)

Figure 2.6: Relay 48.61

CHAPTER 3 METHODOLOGY AND DESIGN

First of all, the design explained on the following pages regards the hardware design part. The software design and its implementation will be carried Miquel Ribalda and it will be explained in his report. The cause of this split of tasks is the scope was very large for one single student.

During the realization of the project, different solutions have been studied. In this chapter, it is going to be analyzed the pros and cons of every design proposed. It has to be taken into account that the operator does not know how the whole system works internally. In fact, the operator just need to learn how the system works to carry properly the calibration process and it should be very easy to understand it. That's why, the structure has been designed as modular as possible and *plug and play*.

At first, the whole circuit design will be split into three different parts:

- Power supply box
- Control box
- Feedback box

Furthermore, it will be explained and tested the test bench construction, including which pipes has to be used and measurements.

3.1 Power supply box

In the power supply box, as its name indicates, will be mounted a system to supply the whole system. The system includes control box, feedback box and the devices to be calibrated, in this case four.

The requirements of this power supply box , in terms of voltage levels, are the following:

- The valves need to open or close 24 VAC. Therefore, this voltage must come from this box.
- The relays selected switch when the voltage drop in the coil is 24 VDC, so the box must provide this required voltage.
- For the manual mode explained in the introduction, it will be used 5 VDC. The reason will be explained in the control box section.

Once the basic requirements have been chosen, requirements in terms of safety and physical design also must be fulfilled to get a professional product. These requirements are the following:

- Electromagnetic compatibility (EMC) protection. The whole supply must be protected against EMC issues coming from the electric grid or other external sources.
- Over power protection. A circuit breaker is included in order to control the maximum power providing from the grid.
- Easy of use. In order to get an organized box, a distribution board will be used.

3.1.1 24 VAC

At this point, it is clear what is needed to include in the power supply box. In order to get 24 VAC, two transformer [4] *Isolated DIN rail transformer* was chosen. It has been ordered 2 because one of them does not provide enough power to supply 8 electric valves. One valve has a power consumption of 10 W, so 8 valves will consume 80 W. At least, 80 Volt Ampere (VA) it is needed to be sure to provide power enough to activate the valves.

The reasons to pick this transformer are because of it includes a DIN rail, which it is very useful to organize this kind of components, and a 3.15 A fuse for its own protection. Hence, there is no need to include a fuse in the system. Technical details are specified below:

- 230 VAC primary winding, 24 VAC secondary winding
- Power: 20-75 VA
- Isolation: 4 kV RMS
- Width x Height x Depth: 160 x 90 x x58 mm
- Weight: 1.75 kg

Figure 3.1: 24 VAC transformer

3.1.2 5 VDC

The 5 VDC only are needed for valves switching via manual mode (explained in control box section) and, if any, to supply integrated circuits for future modifications and/or expansion. The unique requirement fulfilled to include a 5 VDC source is that includes also a DIN rail. The source selected is *Single Output Industrial DIN Rail Power Supply DR-15 Series* [5]. Technical details are specified below:

- Input voltage: 230 VAC
- Output voltage: 4.75 VDC to 5.5 VDC
- Output maximum current: 2.4 A
- Ripple: 80 mV peak to peak (pp)
- Dimensions: 56 x 25 x 93 mm
- Temperature range: -20°C to 60°C
- Short circuit, overload and over voltage protection

Figure 3.2: 5 VDC power supply

3.1.3 24 VDC

As it has been explained before, the 24 VDC will be used to supply 8 devices and 8 relays. In order to know which power supply should be used, some calculations are needed. The maximum current consumption for one device is 891 mA. So that, 8 devices have a current consumption of 3.57 A. Moreover, the relay has also a current consumption that must to be taken into account. According to the datasheet [3], the current consumption while 24 VDC drops across its coil ports is 22.2 mA. Hence, the total 8 relays current consumption is 177.6 mA. To sum up, the minimum current that the power supply must provide is 3.7476 A.

The power supply chosen is *S-100F-24*, which it converts from 230 VAC to 24 VDC providing 4.5 A as maximum, enough for our purposes. Furthermore, this power supply is very widely used in the company so to acquire one is very fast. More technical details are specified below:

- Input voltage: 230 VAC
- Output voltage (2 outputs): 24 VDC
- Output power: 108 W
- Maximum output current: 4.5 A
- Length x Width x Height: 199 x 98 x 38 mm

Figure 3.3: 24 VDC power supply

3.1.4 Circuit breaker

This circuit breaker [6] is included for two reasons: to control the amount of power is coming from the electric grid and to turn on and off easily the whole supply system. In this case, it us allowed to pass 1 A as maximum. More technical information are specified below:

- Rated operational voltage: 250 VAC 50/60 Hz or 48 VDC
- Mechanical durability: 8000 cycles
- Electrical durability: 8000 cycles
- Maximum output current: 1 A
- Height x Width x Depth: 74 x 15 x 67 mm

Figure 3.4: Circuit breaker

3.1.5 AC filter

An AC filter [7] has been included because of the necessity to protect the supply against any interference voltage from the mains. In this case, the filter provides symmetrical and asymmetrical attenuation in the frequency range from 10 kHz up to 30 MHz. The maximum nominal current is 1 A, chosen because of the circuit breaker provides this maximum current already. Moreover, a DIN rail is included for easy implementation. Since the circuit breaker allows to pass 1 A as maximum the figure 3.5 shows the attenuation loss at 1 A.

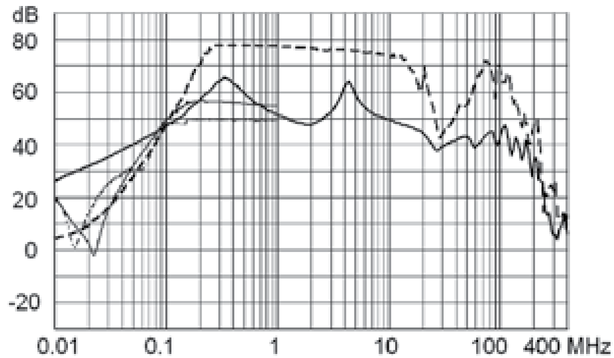
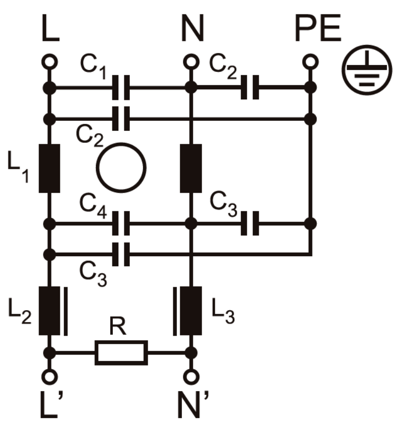


Figure 3.5: 1 A attenuation loss

The model selected has the schematic represented in the figure 3.6a, and physically the filter looks like the figure 3.6b.



(a) Filter schematic

(b) Filter

Figure 3.6: Grid filter

3.1.6 Connectors

All the signals generated within the box shall be brought to every part of the system designed. So that, panel connectors and suitable cables shall be included. On the connectors side, it must be one single kind of connector for one determined signal, based on poka-yoke technique [8]. In this case, 5 VDC, 24 VDC, 24 VAC are different connectors, while 230 VAC as input is other connector. The connectors are the following ones:

- For 5 VDC and 24 VDC share the same connector and ground. By this way, the all VDC signals have the same reference. The male connector used is 4 pins XLR connector, represented on the figure 3.7b. A female 4 pin XLR connector has been used as a cable (Figure 3.7a). The pinout is explained on the table 3.1. The number of connectors placed in the power supply box is 2: one for control box and other one to supply the devices to calibrate.
- For 24 VAC, it has been used 3 pin XLR male connector 3.8b (the female one for the cable 3.8a). The pinout is explained on the table 3.2. It has been placed 2 male connectors, one for each transformer.

- For 230 VAC input, the connector selected is a common AC power entry.

(a) 4 pin female XLR connector

(b) 4 pin male XLR connector

Figure 3.7: VDC connectors

(a) 3 pin female XLR connector

(b) 3 pin male XLR connector

Figure 3.8: VAC connectors

5 VDC/24 VDC - 4 PIN XLR	
Pin number	**Signal**
1	5 VDC
2	GND (From 5 VDC supply)
3	GND (From 24 VDC supply)
4	24 VDC

Table 3.1: 4 Pin XLR connections

24 VAC - 3 PIN XLR	
Pin number	**Signal**
1	Neutral VDC
2	Phase
3	Ground

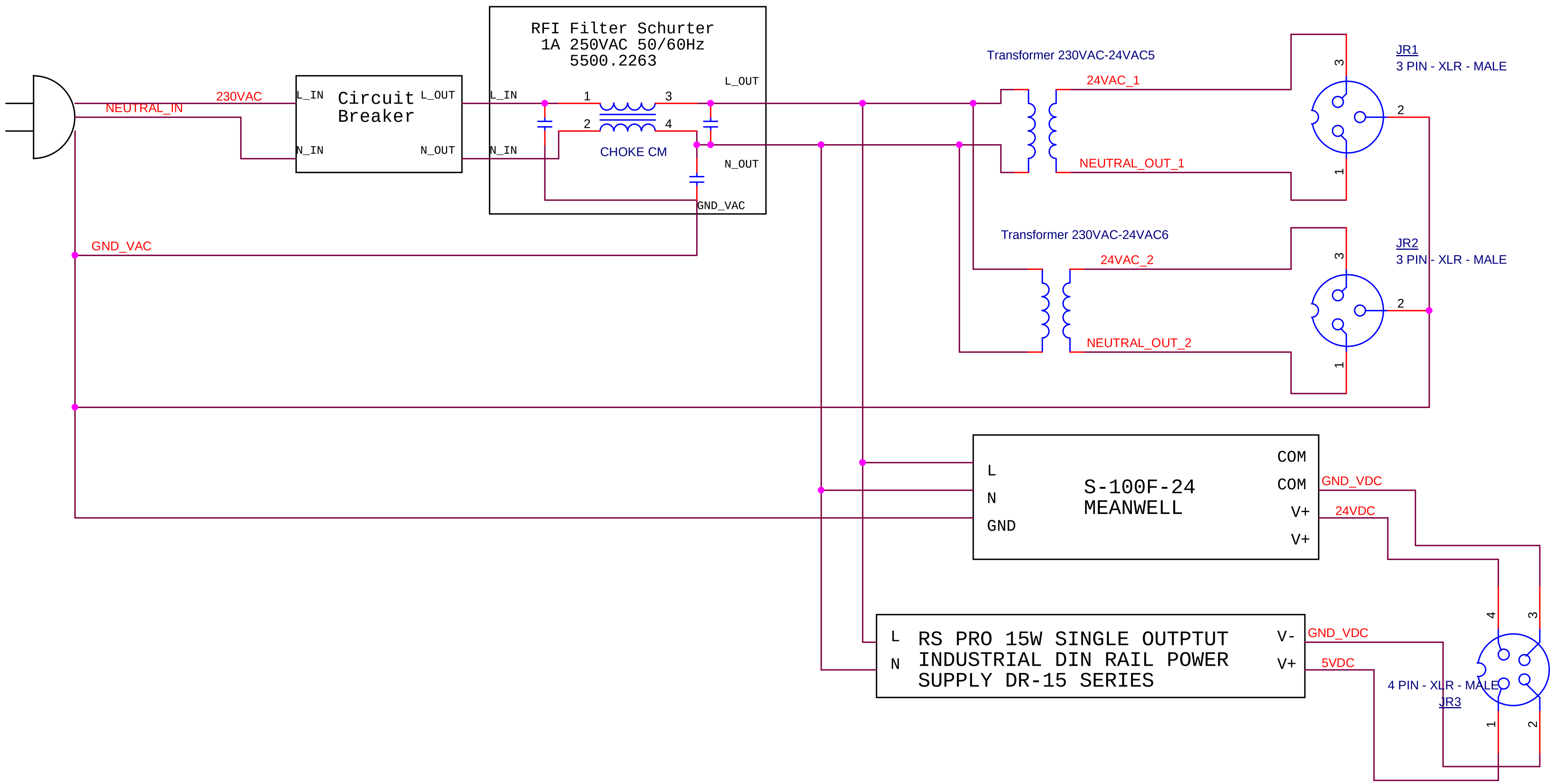
Table 3.2: 3 Pin XLR connections

3.1.7 Connections and distribution board

Once it has been chosen all the components to fit inside the distribution board [9] (Figure 3.9), it is time to assemble all together. To make all the connections, 1.5 mm copper cable has been used, which its maximum current flow is 11 A, enough for our purpose. Furthermore, the distribution board provides many connection ports and there are three parts internally connected. These parts will be used to connect all the phases, neutrals and grounds together.

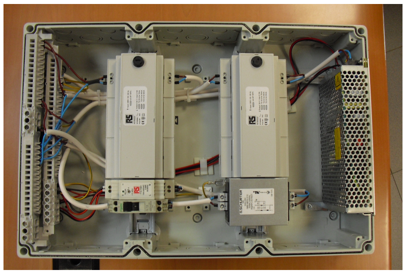
Figure 3.9: Distribution board

On the following page is represented the schematic fulfilled to make all the connections within.


NEUTRAL_IN
230VAC
L_IN
N_IN
Circuit Breaker
L_OUT
N_OUT
RFI Filter Schurter
1A 250VAC 50/60Hz
5500.2263
L_IN
N_IN
1
2
3
4
CHOKE CM
L_OUT
N_OUT
GND_VAC
GND_VAC
Transformer 230VAC-24VAC5
24VAC_1
NEUTRAL_OUT_1
JR1
3 PIN - XLR - MALE
Transformer 230VAC-24VAC6
24VAC_2
NEUTRAL_OUT_2
JR2
3 PIN - XLR - MALE
S-100F-24
MEANWELL
L
N
GND
COM
COM
V+
V+
GND_VDC
24VDC
RS PRO 15W SINGLE OUTPTUT
INDUSTRIAL DIN RAIL POWER
SUPPLY DR-15 SERIES
L
N
V-
V+
GND_VDC
5VDC
4 PIN - XLR - MALE
JR3

It may be discrepancies regarding the 24 VAC pinout explained previously and the showed one on the schematic, in matter of pin numbers. The discrepancy comes from the program used for creates the schematic, since the pin numbers are not the same as the manufacturer specified. The pinout fulfilled is the explained on the tables above 3.2.

Finally, the following figures corresponds to power supply internal connections 3.10a, the front face 3.10b and the entire power box supply with the connectors explained previously 3.10c.



(a) Power supply box internal connections

(b) Power supply box front face

(c) Power supply box and external connectors

Figure 3.10: Power supply box

3.2 Control box

Once all the voltage supplies are obtained, it is may to design the control stage to open or close the valves. It has to be taken into account that, as it has been explained in the introduction, three modes of operation have to be applied. To do that, two possible designs have been presented. Otherwise, the main change in both designs relies on the software operation mode. The remaining two modes are straightforward and the main component used in both designs is an integrated circuit that acts as a relay driver, called ULN2803A.

3.2.1 ULN2803A

The integrated circuit ULN2803A [10] is a transistors array in Darlington format that provides 8 high current outputs. In this case, it has been used PDIP encapsulated one, since the first board, due to lack of time, it will be implemented on stripboard.

Description

This integrated circuit ULN2803A contain 8 Darlington transistors with common emitters and suppression diodes for inductive load. As it is observed in figure 3.11 , each driver contains an input resistance of 2.7 kΩ to limit the current, so there is no need to put an input resistance for current protection purposes.

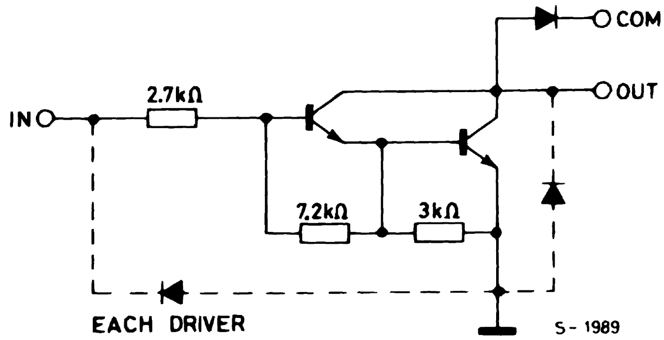


Figure 3.11: ULN2803A driver

The way to use this integrated circuit is as follows [11]. As it is known, a relay shall be activated by three different modes. To do that, a driver is implemented. The relay has connected the positive pin to positive supply voltage and the negative pin, instead of connect it to the negative supply voltage pin, it is connected to the pin OUT represented in the figure 3.11. So when at transistor input there is a high voltage, the transistor drives current, which it means that the relay's pin connected to the driver output it is connected to ground, closing the circuit. Therefore, if the circuit is closed, the relay switches its position. On the other hand, when at the transistor's input there is a low voltage, the transistor stops driving current and the circuit is open, so the relays switches. This is the way ULN2803A is going to be used, since it is an array of 8 drivers, one for every single relay it is going to use.

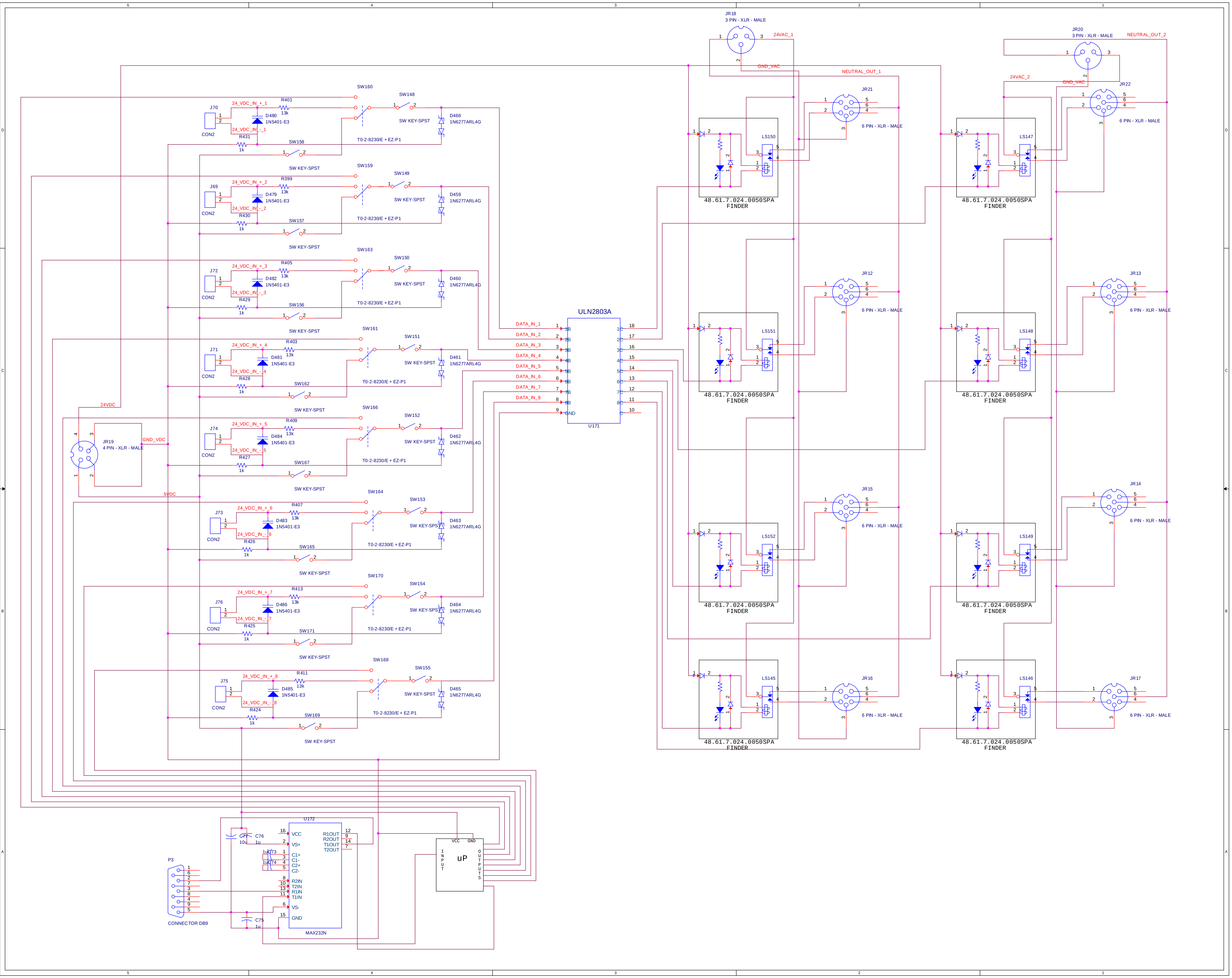
Technical details

In this section is summarized the technical features observed for further explained designs:

- Maximum input voltage: 30 VDC
- Input current: 0.93 mA
- Minimum input voltage: 2.4 VDC

3.2.2 Design 1

Since most of the parts of the circuit are the definitive one, they will be explained in the final design. In this case, it is going to be more focused on the software mode of operation, which is the main difference respect to the other design explained later. First, let's take a look to the schematic.



ULN2803A
U171
MAX232N
U172
uP
CONNECTOR DB9
P3
48.61.7.024.0050SPA FINDER
6 PIN - XLR - MALE
3 PIN - XLR - MALE
4 PIN - XLR - MALE
NEUTRAL_OUT_2
NEUTRAL_OUT_1
24VAC_2
24VAC_1
GND_VAC
GND_VDC
24VDC
5VDC
DATA_IN_1
DATA_IN_2
DATA_IN_3
DATA_IN_4
DATA_IN_5
DATA_IN_6
DATA_IN_7
DATA_IN_8
1N6277ARL4G
1N5401-E3
SW KEY-SPST
T0-2-8230/E + EZ-P1
CON2

In this case, the way to connect the control box and the computer is done through a RS232 port or also known as Serial Port. Furthermore, it is included a microprocessor to read data from the serial port reading one single bit. In other words, from the computer is sent 0001 for example, it is sent first 0, then other 0, another 0 and finally 1, instead of send 4 bits at the same time. The microprocessor would need 10 channels at least, 1 input and 9 outputs (one of them as a feedback of received data).

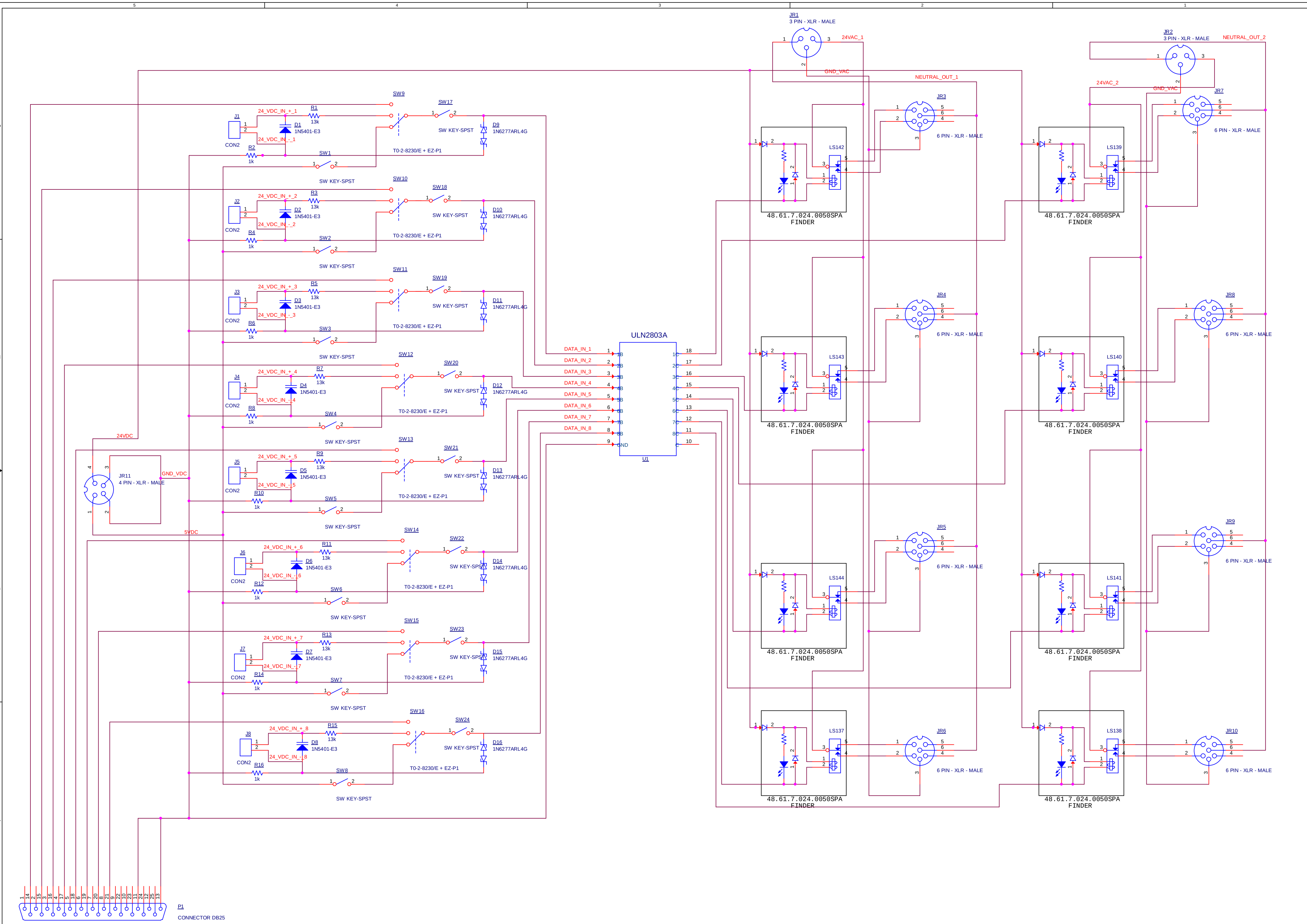
Note that between RS232 and the microprocessor it is placed an integrated circuit, which is a MAX232 [12]. A general purpose microprocessor (for example, a PIC one, very straightforward of use) are able to work with TTL signals, which they are signals that goes from 0 VDC to 5 VDC. The problem is that the Serial Port signals levels goes from -12 VDC to 12 VDC. Here it is found a mismatch between signal levels, so it is needed to put them on the same level. This is the purpose of the MAX232.

The main advantage of this solution is that software application is direct to implement. The microprocessor would be programmed to supply 1 (5 VDC) or 0 logic (0 VDC) depending on the input received. Therefore, from the computer it would be easy to send 1 or 0 through the Serial port by the terminal, for example.

On the other hand, the time to implement this solution is larger, due to PIC programmer misses, no software licence are available to program it and and it would be tough to debug it on board.

3.2.3 Design 2

The following schematic corresponds to the final design that will be developed. In this case, it will be explained every part of the circuit, including the three modes of operation.


ULN2803A
U1
DATA_IN_1
DATA_IN_2
DATA_IN_3
DATA_IN_4
DATA_IN_5
DATA_IN_6
DATA_IN_7
DATA_IN_8
GND
JR1
3 PIN - XLR - MALE
24VAC_1
GND_VAC
NEUTRAL_OUT_1
JR2
3 PIN - XLR - MALE
NEUTRAL_OUT_2
24VAC_2
JR3
JR4
JR5
JR6
JR7
JR8
JR9
JR10
6 PIN - XLR - MALE
LS137
LS138
LS139
LS140
LS141
LS142
LS143
LS144
48.61.7.024.0050SPA
FINDER
JR11
4 PIN - XLR - MALE
24VDC
GND_VDC
5VDC
24_VDC_IN_+_1
24_VDC_IN_-_1
SW KEY-SPST
T0-2-8230/E + EZ-P1
1N6277ARL4G
1N5401-E3
13k
1k
CON2
P1
CONNECTOR DB25

As it is observed, the main difference relies on the software input part. In this case, instead of using the Serial Port - level converter - microprocessor combination, it has being used a parallel port. In this case, while it is sent from the computer logical 1 or 0, it is translated to 5 VDC or 0 VDC respectively. In order to use the parallel port, it is needed another add-on out of the circuit. In this case, it is used the Data Acquisition (DAQ) from National Instruments model NI-USB-6009, which it can be connected to the computer via USB.

Figure 3.12: NI-USB-6009

The main advantage to use it is because of its 12 digital I/O lines (enough channels for activate 8 relays and for a possible valves status feedback), 8 analog channels, the API provided to control it through custom-program and all this features together make the project faster to implement. Finally, to connect the DAQ to the control box, it has been placed the DAQ within a box and connect it to a parallel port, as it is observed on the figure 3.13. The pinout and an extended explanation is found in Miquel Ribalda's report.

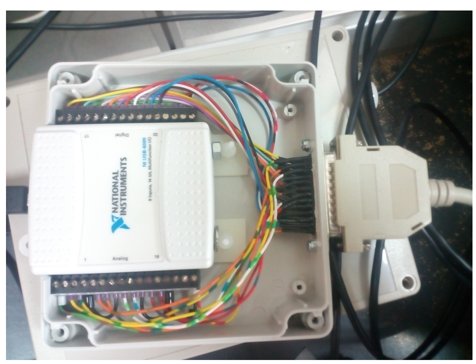


Figure 3.13: NI-USB-6009 and parallel port

On the other hand, the disadvantage of this solution is mainly the cost is increased because of the DAQ and includes another mechanical part to the project, being tougher to handle all the parts together.

Once it is explained the main difference between the 2 designs, it is going to be explained how the remaining operation modes are applied. It has to be taken into account that is needed a certain voltage at the input of the integrated circuit ULN2803A. By thinking further, it is advisable to get in the three modes of operation the same voltage at the ULN2803A input pins, because for a possible feedback design it is desirable to get always the same signal for every operation. In other words, if it is indicating to open the relay, regardless of the operation mode, the signal for open always should be the same. In this case, since the software mode provides 0 VDC and 5 VDC, remaining modes shall provide the same voltage as well.

24 VDC mode

In 24 VDC mode, since it is not supplying anything within the circuit, in order to step down the voltage to 5 VDC, a simple voltage divider it has been used. It has to be taken into account that the ULN2803A has an internal resistance, so the voltage divider will be composed by one single resistor. In this case, the value that provides 5 VDC at the integrated circuit input pins is 13 kΩ. According to he schematic, the resistors R1, R3, R5, R7, R9, R11, R13 and R15 form the voltage dividers for every input. These resistors combination provides the desired 5 VDC and a ULN2803A input current of 1.21 mA, enough for its proper behavior.

It has to be kept in mind that this voltage comes from a source out of the system via terminal blocks, so it is needed to include security elements for circuit protection. It has been placed a voltage reverse protection diode [13], in order to avoid damage the circuit if the operator connect the 24 VDC reverse polarized. So when the input is polarized correctly, the diode does not act, but if the input is inverse polarized, the diode creates a short-circuit that avoid this wrong connection. The diodes with this functionality are D1 to D8 and the model selected is 1N5401-E3, which its breakdown voltage is 100V. Another security element are the resistors R2, R4, R6, R8, R10, R12, R14 and R16, which its main functionality is to avoid to produce a spark when the terminal block is reverse polarized, since it has been connected a positive voltage directly to ground. These resistors have a value of 1 kΩ.

Manual mode

In this mode of operation, it will be used SPDT ON-ON toggle switches (as shown in figure 3.14) to carry 5 VDC at the ULN2803A input to relay's NO position or 0 VDC to relay's NC. These switches, labeled as SW1 to SW8 on the schematic, supports a nominal voltage of 28 VDC and 5 A, enough for our purposes. These 5 VDC comes from the power supply box. This is the reason why 5 VDC power supply was included and, also, for further designs it may be used to supply different integrated circuits or for other purposes.

Figure 3.14: On-On toggle switch

3.2.4 Mode junction

Once it is known how to get 5 VDC at the integrated circuit input for each mode of operation, the three modes together have to be joined at the ULN2803A input. Therefore, the way to join them is using a switch providing 3 inputs and one single output. In order to provide a handily switch for the operator, it has been chosen a rotatory switch. In our case, the model T0-2-8230/E + EZ-P1, which supports up to 20 A, enough for project purposes, is the chosen one (shown in the figure 3.15). These rotatory switches are labeled on the schematic as SW9 to SW16.

Figure 3.15: Rotatory switch

After the rotatory switch, it has been placed two more elements for every channel. One of them is an ON-OFF toggle switch to turn on/off the channel if needed. The other element is a Transient Voltage Suppression (TVS) diode [14] for ULN2803A protection. As it is known, the maximum voltage allowed at the input pins is 30 VDC, so electrostatic discharge may damage the integrated circuit because the voltage may reaches up to kV, larger than 30 VDC. So the diode selected is 1N6277ARL4G model, which its maximum breakdown voltage is 25.2 VDC. Therefore, when a voltage at these nodes are larger than 25.2 VDC, the diode act as a short-circuit to ground, avoiding to damage the integrated circuit. Besides, the input signals to activate the relay are 5 VDC, so the diodes do not affect to the expected behavior. Finally, these TVS diodes are labeled as D9 to D16.

At this point, the design it is already explained by itself. When 5 VDC reaches at the ULN2803A input, its respectively output connects its load to almost directly to ground. This connection switches the relay position and it links the 24 VAC to NO position. Otherwise, if 0 VDC reaches the ULN2803A pins, the 24 VAC COM pin of the relay is connected to NC. The process is the same for every channel.

The relays are connected to 6 male pin XLR and they are connected to the valves. Note that there are two pins not connected to anything. These pins would be used for valve feedback state but because of lack of time, it couldn't be developed. In this report will be presented some solutions for the feedback design.

Regarding the valve connections to 6 male pin XLR, they are showed in the table 3.3:

Valve signals - 6 PIN XLR	
Pin number	**Valve signal**
1	Line CCW
2	Line CW
3	Ground
4	CCW feedback
5	CW feedback
6	Neutral

Table 3.3: 6 Pin XLR connections

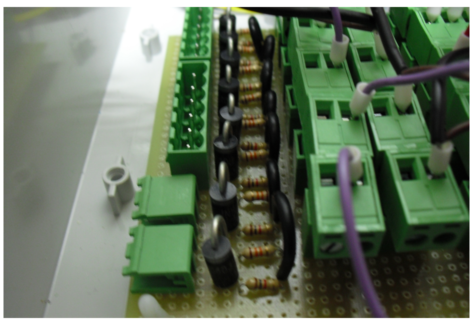
Note that the color of each row corresponds to the color of the cable of the valve.

3.2.5 Assembly

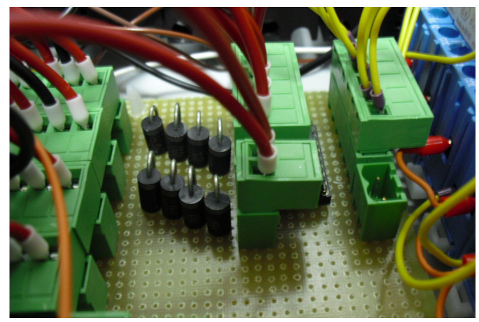
The design 2 was the chosen one and it has been developed. To do that, everything must fit within a box, embed all the connectors to the box and design physically the design selected. It has to take into account that within the box shall fit the electronic circuit, XLR connectors coming from the power box supply, the relays on a DIN rail and the switches explained before.

The electronic circuit has been implemented on a strip board. At first instance, it was desired to design a Printed Circuit Board (PCB) but finally was chosen to do manually on a strip board to start the tests as soon as possible. The dimensions of the strip board are 155x100 mm, enough to put in all the components together. Since there are many connections to switches or other out of the board components, terminal blocks were selected to make the connections properly.

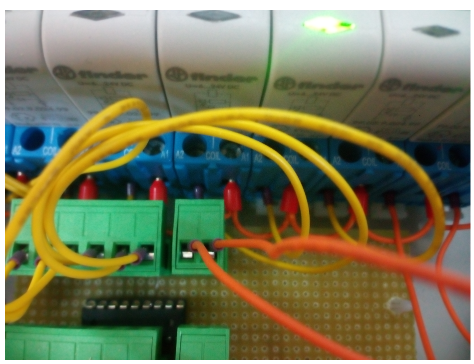
It is not possible to show a figure with the whole electronic circuit assembled, since no pictures were taken and the day these lines are being typed, the control box is already assembled. Otherwise, it can be showed parts of the circuit individually. In the figure 3.16a it is showed the input terminal blocks for 24 VDC, the reverse protection diodes and the voltage divider resistors and protection against spark resistors. Note that the right side terminal blocks are being used for connecting to external switches and the left side terminal blocks will be used to connect 24 VDC. It has been used different type of terminal block to save space, that's why it is used 6 pin and 2 pin terminal block instead of many 2 pin or 4 pin terminal blocks (6 pin terminal blocks were the largest ones found in the company). Furthermore, on the figure 3.16b it is may observe the TVS are placed, the ULN2803A finally assembled, terminal blocks to bring the signal from the rotatory switch to integrated circuit input and from integrated circuit output to relay coil pins, also showed on the figure 3.16c. Finally, the control board has been assembled into control box by using sticky posts.



(a) 24 VDC input



(b) TVS diodes and ULN2803A



(c) Relay coil input

Figure 3.16: Control circuit board

To connect all the components to the switches, it has been used 0.75 mm cables, that supports up to 300 VDC and 6 A, enough for the requirements. Furthermore it has been included 6 male pin XLR on the edge of the box to connect the valves, which they will be connected to the female version. The valve connectors are represented in the figure 3.17.

(a) 6 female pin XLR connector

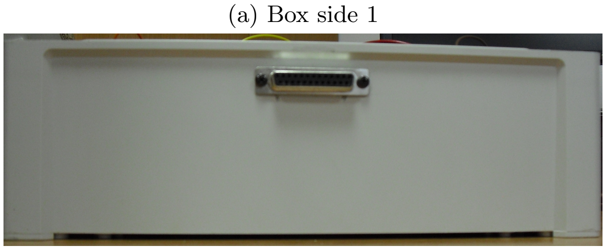
(b) 6 male pin XLR connector

Figure 3.17: Valve connectors

Besides, it has to be included the 24 VAC connectors, 5/24 VDC XLR connectors, toggle and rotatory switches and parallel port as well. All these elements will be fit in a ABS box, which its size is 344 x 289 x 11.74 mm. It will be done all the wholes manually. The final result is represented on the following figures. The figure 3.18a represents the valves connectors, the figure 3.18b represents the 24 VAC, 5/24 VDC connectors and the 4 rotatory switches which their toggle switches for control manually and turn on or off every channel independently, the figure 3.18c represents the parallel port connector and finally, the figure 3.18d represents the switches to control the 4 remaining channels. Note that there is no connection in the cover, because by this way, if the box is needed to be open there will be no elements that makes difficult the inspection.

(a) Box side 1

(b) Box side 2



(c) Box side 3

(d) Box side 4

Figure 3.18: Control circuit board

On the figures above, there is no slot for 24 VDC input. Although the circuit has been designed to support three modes of operation, the 24 VDC mode is not essential, so it has been decided if the operators do need this mode of operation, a new hole will be enabled for this purpose.

Furthermore, different modes of operation may be selected by using rotatory switch. The different modes of operation are summed up below:

- Position 1: 24 VDC mode
- Position 2: manual mode
- Position 3: automatic mode

On the following figure 3.19, it may observe the entire inside box. Note that below the XLR connectors, there are two small boards. The board under supply connectors is designed to join the VDC grounds and for making the connections easier. Besides, the board under the valve connectors are designed to join neutral and grounds of each VAC connectors.

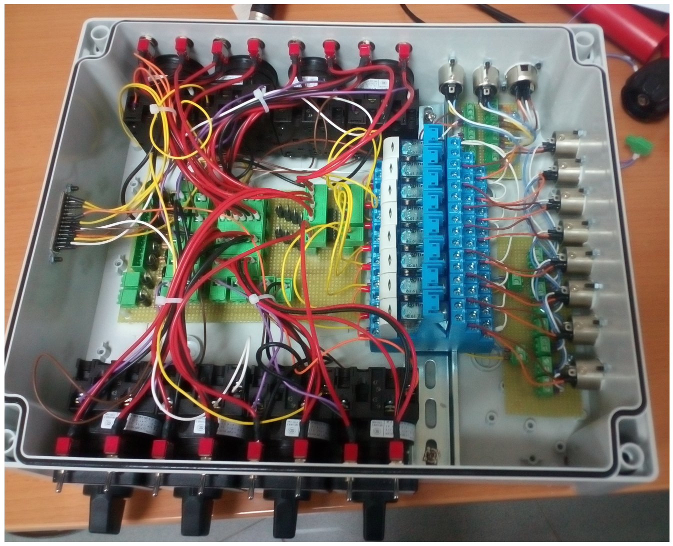


Figure 3.19: Inside the box

Finally, the following figure 3.20 represents the connections between the control box and the power supply box. Note that there is no way to connect them wrong because of the election of different connectors for different purposes.

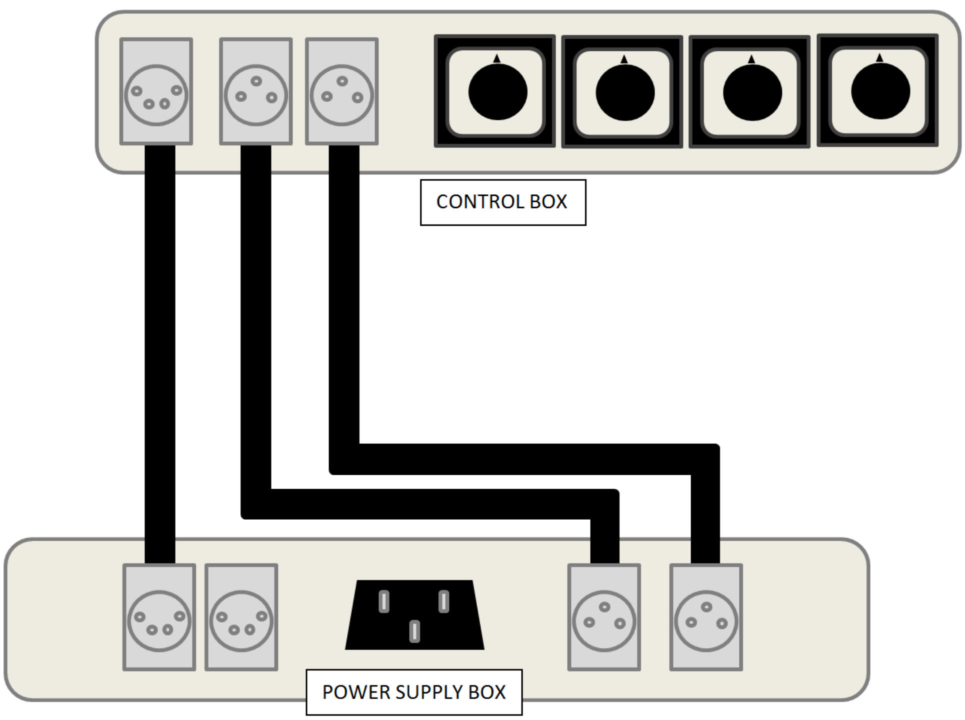


Figure 3.20: Inter box connections schematic

3.3 Feedback design

The control box does not provide any signal that indicates the calibration status, so a feedback box was desired to develop. Because of lack of time, the feedback box could not assemble but it will be shown 2 designs to take into account for future modifications or test bench versions.

Basically, the feedback signal will be sent to DAQ and it will be decide if the calibration process is going correct or not. It will be used 8 digital channels for the valves control and 8 analog channels to send a feedback signal. Before to send the feedback signal, signal conditioning shall be designed to get a proper signal to be read by NI-USB-6009. The analog channels have a resolution of 14 bits, so that the minimum step voltage able to read is $\frac{1}{2^{14}} = 61.03\mu$V.

In order to create the feedback signal, 4 signals have to be brought to feedback box from control box: CW feedback, CCW feedback, DATA-IN-X (where X goes from 1 to 8) and neutral signal. Both valve feedback signals, provides 24 VAC voltage when they are indicating their position. In other words, if the valve is moving, for example, in CCW way, when it reaches its final position, the voltage across that pin and neutral is 24 VAC. The pins called DATA-IN-X are brought to compare if the information sent to the valves corresponds to the valves position have to be. And finally, the neutral signal is needed for signal conversion, since VAC signals are being used.

As same as the control box, part of the circuit is the same one for both designs, which is the part that the signal to be sent through parallel port is processed. The different designs consists on two ways to convert 24 VAC to stable -5 VDC. It has being used -5 VDC because of the shared solution, which will be explained after.

The first design presented is the simplest one. As it can be observed on the figure 3.21, a similar relays used in the control box can useful for this purpose. Otherwise, it should be other relay version, is to say, one that switches when the voltage drop across their pins be 24 VAC. The model is 48.61 AC version.

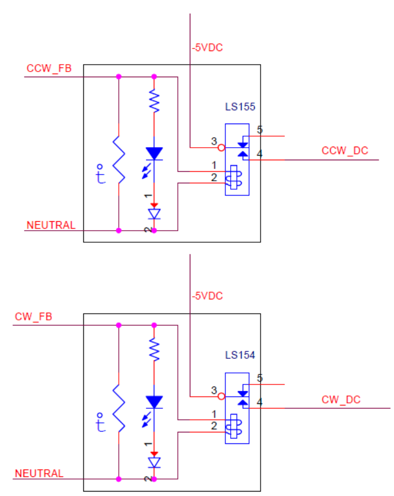


Figure 3.21: Feedback solution 1

As it is observed, -5 VDC is connected to the COM relay's terminal and it turns 24 VAC to - 5 VDC. The main advantage of this solution is that it is very easy to implement. On the other hand, the disadvantages that solution shows are the size of the whole systems and a considerable cost increase because of the components and the new power supply able to provide -5 VDC. Furthermore, the relay solution would include 16 relays, 1 for each state for each valves, taking up a high amount of space.

Other solution proposed is the represented one on the figure 3.22. In this case, it has been placed a diode bridge for every state of each valve, a high capacitor value to reduce the voltage ripple at the output and a voltage divider, using high value resistors to avoid load effects, to get 5 VDC from 24 VDC after the diode bridge.

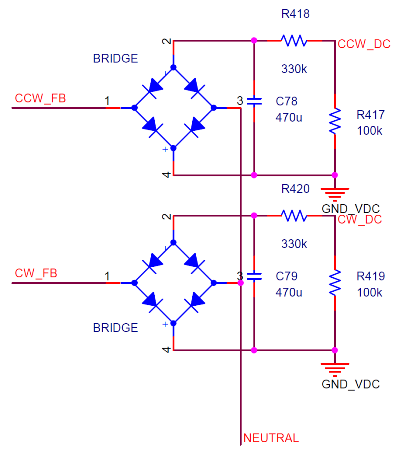


Figure 3.22: Feedback solution 2

Mainly, the advantage of this solution relies on the small size of the components to be used and the cost. All the diode bridges can be placed in one single board, along the capacitors and resistors. This was not possible using the relay. On the other hand,the disadvantage is that the solution has more than one single component, so it is not such easy to implement as the relay's solution.

Until this point, there are two designs to take into account in terms of voltage conversion. As it has been explained before, the step to turn all the signals into one useful single signal to know the valve status is the same one for both designs. The idea is represented on the following picture 3.23. The circuit represents, actually, a Digital Analog Converter (DAC) converter, to convert from -5 VDC and 0 VDC to a signal, which its own range goes from 0 VDC to 5 VDC span.

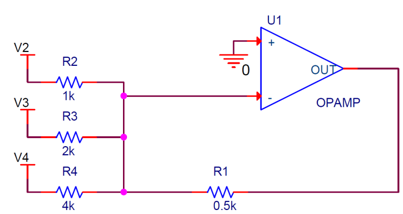


Figure 3.23: Signal conversion to DAQ

The election of -5 VDC comes from the inverter operational amplifier, since in order to apply this solution, the input signal range goes from -5 to 0 VDC and the operational amplifier is supplied by 5 VDC. It cannot be other combination since the DAQ does not read negative analog signals.

V1, V2 and V3 represents the CCW, CW and DATA-IN-X signals, which their own range goes from 0 to -5 VDC. After that, the voltage is decreased used different weights, which in this case are the resistors. As it is observed, the resistors are the first resistor multiplied by 2 for every resistor placed, as common DAC works. Then at the output, it will be obtained an analog signal, that it will brought to parallel port connector, providing the feedback signal. As it is observed in the simulation represented on the figure 3.24. The steps are higher than the 61.03μV, so that the DAQ can read every combination of the feedback signals and decide when the valve's status are wrong.

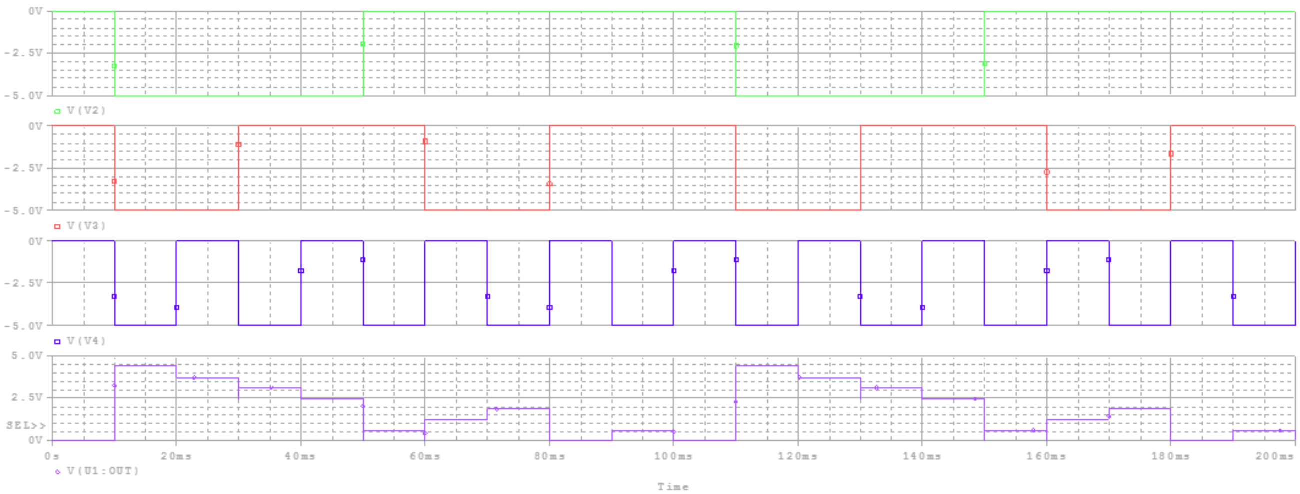


Figure 3.24: Simulation results

3.4 Test bench design

Once it is designed all the hardware part, the new test bench will be assembled. Remembering the specifications explained at the introduction, it is desired to fit in one single test bench 4 devices to be calibrated. One of the limitations that it has to be taken into account, is the space available. In this case, the dimensions of the test bench are represented on the following figure 3.25. It should be included the distance from the floor to the ceiling, which is 300 cm.

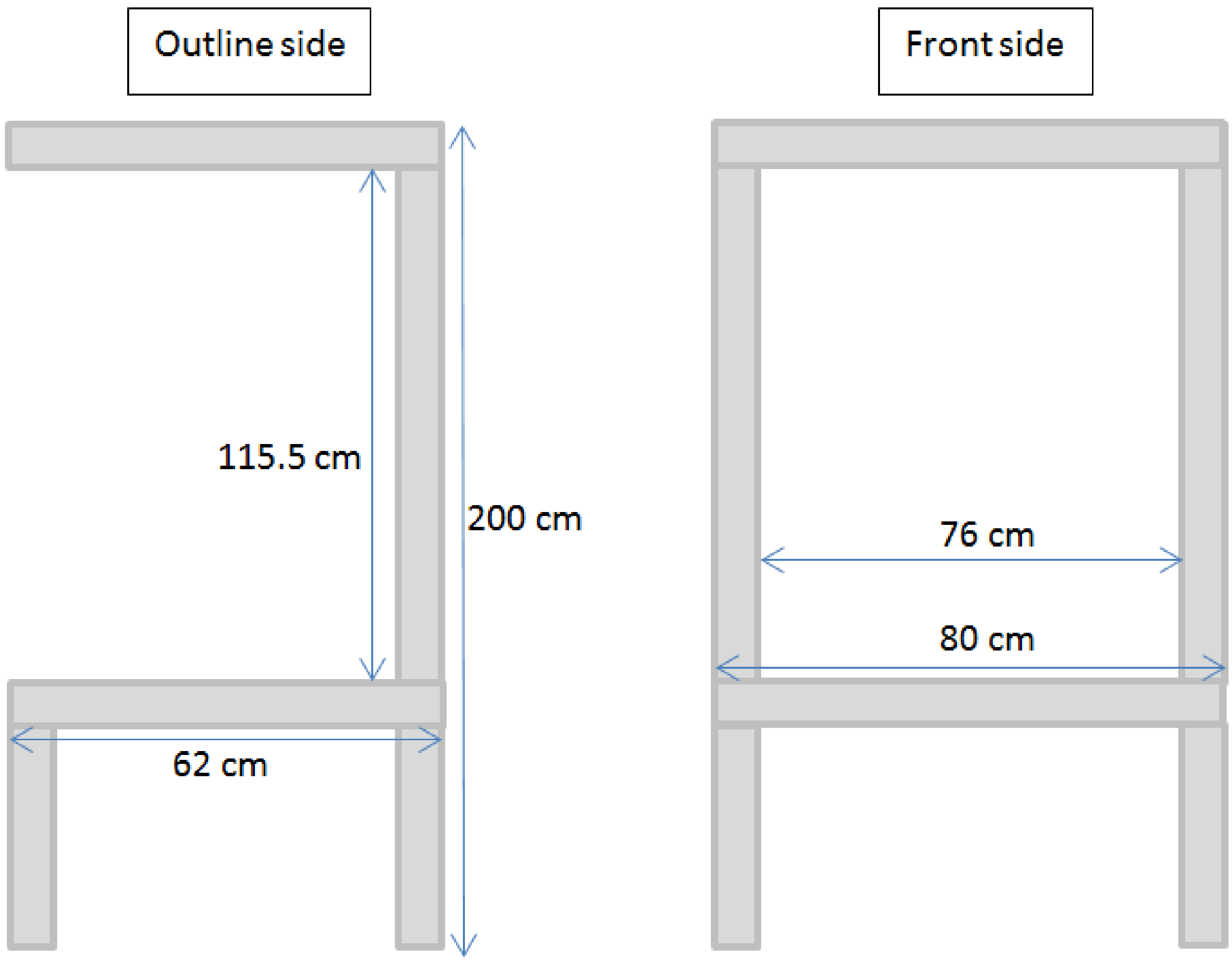


Figure 3.25: Test bench dimensions

In order to assemble the valves, the pipes and the probes some designs were tested to study the air flow. This study is necessary in order to do the pipes long enough to avoid turbulence in the junctions and short enough to get minimum air flow losses due to pipe friction. The first thing to test are the minimum pipe longitude before the probe. There should be a minimum pipe distance to avoid disturbance in the air flow measurement. To know it, it has been measured the air flow between two probes, testing different pipe length. The table 3.5 represents the pipe length measurements (figure 3.26) and the probe readings. The readings are not important, only the difference between them is taken into account.

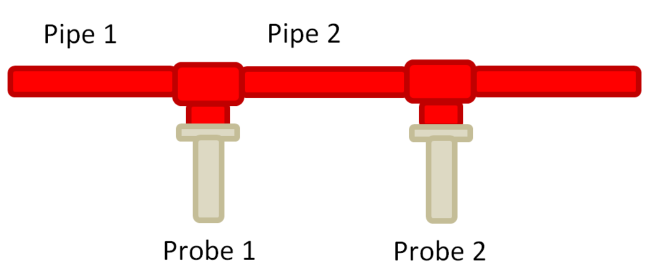


Figure 3.26: Probe positions and pipe length

Pipe length 1	Pipe length 2	Probe 1 measurement	Probe 2 measurement	Difference
30	30	1.69	1.98	0.29
30	50	1.88	1.99	0.11
50	30	1.85	1.99	0.14
50	50	1.84	1.98	0.14

Table 3.4: Pipe length test

It is observed that the proper length before probe readings is 50 cm, since it provides the best results, is to say, the value read in the probe 50 cm before is very close the read one in the probe 50 cm placed after.

Another thing to take into account is the losses due to pipe length. This data is needed to demonstrate that the pipe losses are not negligible, so the pipe length cannot be too much long. To guarantee the readings validity, the probe will be placed at the beginning and at the end of the pipe, which is the schema represented on the figure 3.27 and the results are represented on the table 3.5.

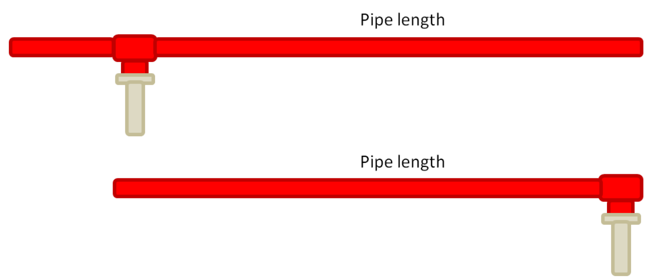


Figure 3.27: Pipe losses demonstration test

Pipe length (cm)	Probe reading short pipe (m/s)	Probe reading short pipe (m/s)
220	5.65	5.7
270	5.58	5.53

Table 3.5: Pipe length test

As it is observed in the results, the probe readings provides almost the same value without depending its positions and it can conclude that the pipe length does affect to the probe readings, so that the pipe length in the final test bench cannot be very long.

Once it is known the minimum pipe length to get minimum turbulence and the pipe length cannot be too much long, it is going to assemble the test bench. First, it has to take into account the pipe diameter. The valves have a connector with an external diameter of 25 mm but the pipes used in the company have 27 mm diameter. Therefore, 25 to 27 mm adapters are needed to assemble the pipes and the valves. Furthermore, two probes are embed to read the air flow, one for reading until 1 m/s providing a higher accuracy and other one to read higher air flows. These probes are connected to an ALMEMO 5690-2 datalogger, represented on the figure 3.28 and detail explained in Miquel Ribalda's report. Finally, to control the air flow, end caps are placed at the end of the pipe, which depending on the diameter, the air flowing through would be higher or lower.

Figure 3.28: Datalogger Almemo 5690-2

In a first try, it was desired to create one single line for every device to be calibrated, as the figure 3.29. But there was a problem and it was that the maximum air flow reading did not reach 6 m/s, needed for a proper calibration. The problem was found in the valve's internal connector, which the reduction of the air flow is not negligible. The air flow with the same pipe length without valve was measured and more than 1 m/s was lost due to valve connectors. In order to get the desired air flow, the pipe were cut to reduce the pipe losses, but it was not possible to reach 6 m/s keeping correct readings on the anemometer.

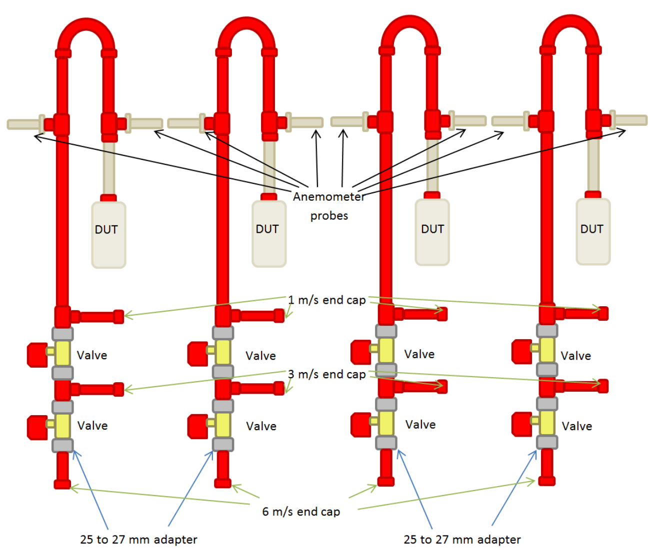


Figure 3.29: First design test bench

Therefore, the solution was to include another line as an input, controlled by the valve as it is shown on the figure 3.30, including all the measurements. By this way, it was able to get more than 6 m/s, so that the device calibration could be successful in terms of air flow needed. Note that in both designs, at the end of the pipe circuit, there is a flexible pipe to make easier to push in or pull out the pipe into the device to calibrate. Furthermore, the two probes are included in both designs.

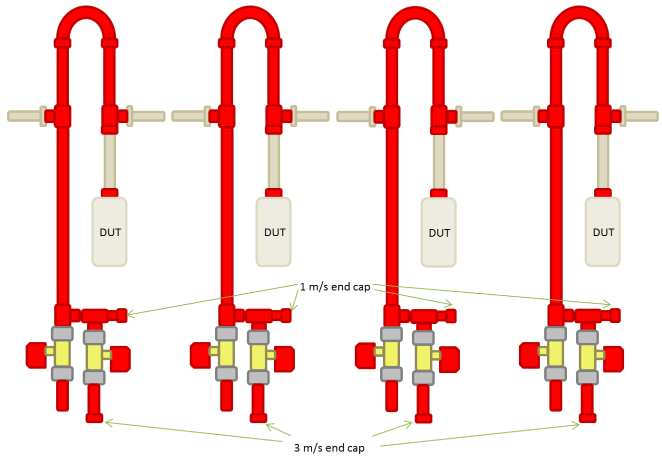


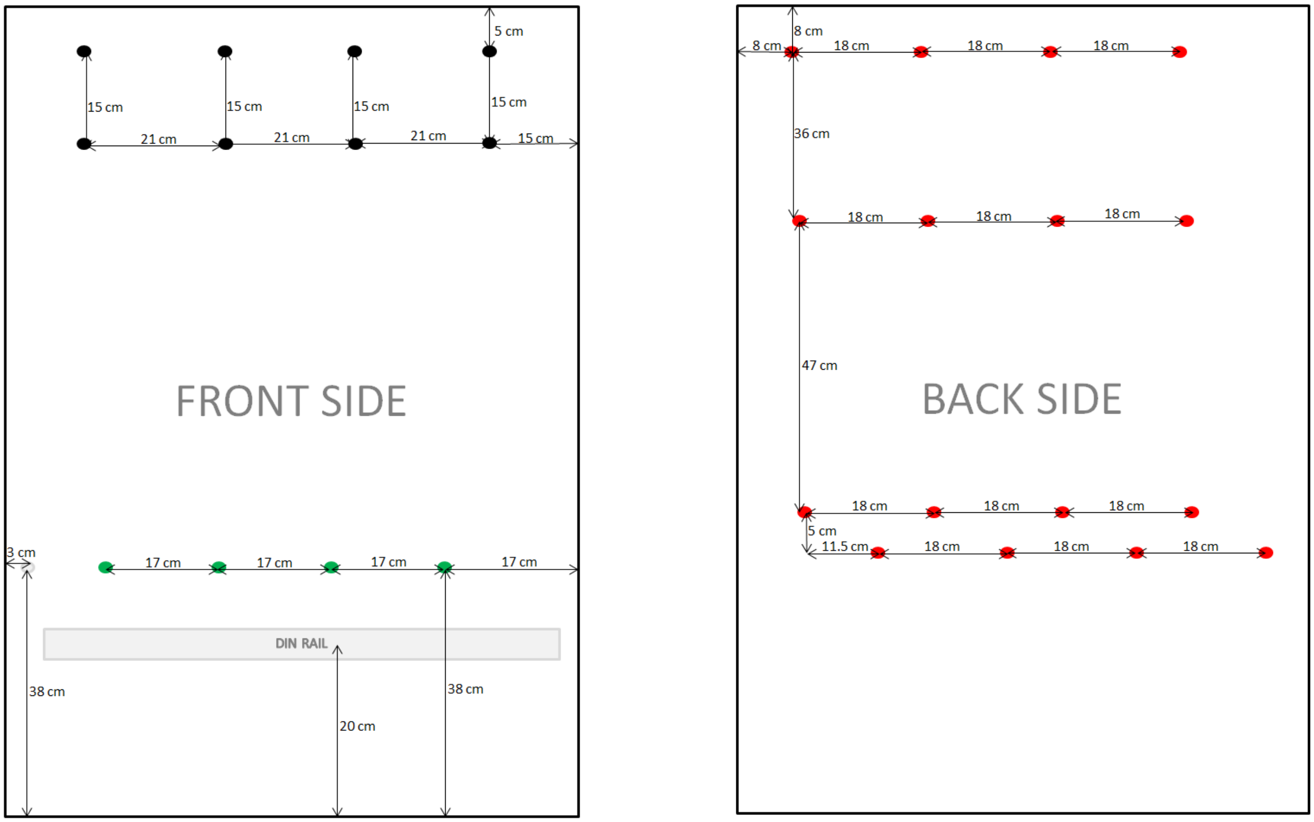
Figure 3.30: Final design test bench

3.5 Test bench assembly

Once it was known that the design explained worked properly, the assembling was the next step. The materials used to assemble the pipes, the valves and the devices to be calibrated are:

- 2 DIN rails to hold the devices to be calibrated.
- 4 screwier 3mm and their corresponding nuts. They have been used to affix the DIN rails.
- 16 screwier 5mm and their corresponding nuts. They have been used to affix clips without screwier (red holes in figure 3.31).
- 16 clips without screwier to hold the pipes.
- 8 clips with 8mm screwier and their corresponding 2 washers and nuts for each clip (black holes in figure 3.31).
- 1 XLR connector 4 pin male to supply the 4 devices to be calibrated (gray holes in figure 3.31).
- 1 wood to assemble everything on it. 120 x 85 cm.
- 4 switches 20mm to turn on or off the devices to plug it or plug out (green holes in figure 3.31).

Furthermore, 4 more 6 mm diameter holes have to be made to pass the wires to connect the devices to the computer through RS485. Following the schema represented on the figure 3.30 and the schema represented on the figure 3.31 to make the holes correctly at the desired distance, the final result are shown on the figure 3.32 corresponding to the front side and on the figure 3.33 corresponding to the back side.



(a) Front side

(b) Back side

Figure 3.31: Holes on the wood

Figure 3.32: Front side test bench

Figure 3.33: Back side test bench

CHAPTER 4

RESULTS

In this chapter, it will be explained the results regarding the valves behaviour according to the commands sent by control box and the main changes regarding the calibration process explained in previous chapters. The device calibration results have been analyzed by Miquel Ribalda, who has been responsible of calibration results analysis.

4.1 Valves behaviour

In order to know if the valves state corresponds to the command sent, the following steps will be fulfilled:

- Open and close valve 1 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 2 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 3 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 4 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 5 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 6 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 7 and measure its state changing time. Check if the remaining valves keep their state.
- Open and close valve 8 and measure its state changing time. Check if the remaining valves keep their state.

On the table 4.1, it can be checked the results applying the steps explained before. With these results, it is may conclude that the valves responds correctly to the signals sent, but another analysis will be carried. In this case the analysis, more exhaustive, consists on check the possible 256 valves combination and measure the time changing from one combination to the next one. On the following pages, it can be checked the results of this exhaustive analysis. On the tables, 0 means close valve and 1 means open valve.

Valve 8	Valve 7	Valve 6	Valve 5	Valve 4	Valve 3	Valve 2	Valve 1	Time
0	0	0	0	0	0	0	0	-
0	0	0	0	0	0	0	1	16.22
0	0	0	0	0	0	1	0	16.12
0	0	0	0	0	0	1	1	16.28
0	0	0	0	0	1	0	0	18.61
0	0	0	0	0	1	0	1	18.39
0	0	0	0	0	1	1	0	16.93
0	0	0	0	0	1	1	1	19.82
0	0	0	0	1	0	0	0	17.14
0	0	0	0	1	0	0	1	17.16
0	0	0	0	1	0	1	0	18.49
0	0	0	0	1	0	1	1	17.88
0	0	0	0	1	1	0	0	18.87
0	0	0	0	1	1	0	1	18.26
0	0	0	0	1	1	1	0	17.9
0	0	0	0	1	1	1	1	18.02
0	0	0	1	0	0	0	0	19.03
0	0	0	1	0	0	0	1	17.17
0	0	0	1	0	0	1	0	16.68
0	0	0	1	0	0	1	1	17.14
0	0	0	1	0	1	0	0	18.25
0	0	0	1	0	1	0	1	18.83
0	0	0	1	0	1	1	0	18.86
0	0	0	1	0	1	1	1	16.46
0	0	0	1	1	0	0	0	18.13
0	0	0	1	1	0	0	1	17.55
0	0	0	1	1	0	1	0	18.11
0	0	0	1	1	0	1	1	18.67
0	0	0	1	1	1	0	0	18.88
0	0	0	1	1	1	0	1	18.82
0	0	0	1	1	1	1	0	18.44
0	0	0	1	1	1	1	1	16.89
0	0	1	0	0	0	0	0	18.26
0	0	1	0	0	0	0	1	18.16
0	0	1	0	0	0	1	0	17.3
0	0	1	0	0	0	1	1	18.48
0	0	1	0	0	1	0	0	16.62
0	0	1	0	0	1	0	1	18.51
0	0	1	0	0	1	1	0	16.82
0	0	1	0	0	1	1	1	16.98
0	0	1	0	1	0	0	0	17.11
0	0	1	0	1	0	0	1	17.03
0	0	1	0	1	0	1	0	16.71
0	0	1	0	1	0	1	1	22
0	0	1	0	1	1	0	0	18.71
0	0	1	0	1	1	0	1	21.12
0	0	1	0	1	1	1	0	18.24
0	0	1	0	1	1	1	1	22.61
0	0	1	1	0	0	0	0	17.34
0	0	1	1	0	0	0	1	19.14
0	0	1	1	0	0	1	0	17.93
0	0	1	1	0	0	1	1	18.63
0	0	1	1	0	1	0	0	17.78
0	0	1	1	0	1	0	1	16.54
0	0	1	1	0	1	1	0	16.92
0	0	1	1	0	1	1	1	17.37
0	0	1	1	1	0	0	0	16.8
0	0	1	1	1	0	0	1	18.52
0	0	1	1	1	0	1	0	16.6
0	0	1	1	1	0	1	1	17.65
0	0	1	1	1	1	0	0	17.13
0	0	1	1	1	1	0	1	18.73
0	0	1	1	1	1	1	0	18.59
0	0	1	1	1	1	1	1	16.93
0	1	0	0	0	0	0	0	18.99

0	1	0	0	0	0	0	1	16.86
0	1	0	0	0	0	1	0	19.07
0	1	0	0	0	0	1	1	17.98
0	1	0	0	0	1	0	0	17.92
0	1	0	0	0	1	0	1	18.28
0	1	0	0	0	1	1	0	16.72
0	1	0	0	0	1	1	1	17.4
0	1	0	0	1	0	0	0	18.28
0	1	0	0	1	0	0	1	18.13
0	1	0	0	1	0	1	0	18.21
0	1	0	0	1	0	1	1	17.29
0	1	0	0	1	1	0	0	21.17
0	1	0	0	1	1	0	1	18.54
0	1	0	0	1	1	1	0	18.43
0	1	0	0	1	1	1	1	18.93
0	1	0	1	0	0	0	0	18.71
0	1	0	1	0	0	0	1	18.48
0	1	0	1	0	0	1	0	17.14
0	1	0	1	0	0	1	1	19.48
0	1	0	1	0	1	0	0	16.62
0	1	0	1	0	1	0	1	18.89
0	1	0	1	0	1	1	0	18.16
0	1	0	1	0	1	1	1	21.62
0	1	0	1	1	0	0	0	17.82
0	1	0	1	1	0	0	1	23.82
0	1	0	1	1	0	1	0	18.83
0	1	0	1	1	0	1	1	17
0	1	0	1	1	1	0	0	17.62
0	1	0	1	1	1	0	1	17.24
0	1	0	1	1	1	1	0	18.39
0	1	0	1	1	1	1	1	18.81
0	1	1	0	0	0	0	0	19.01
0	1	1	0	0	0	0	1	21.01
0	1	1	0	0	0	1	0	17.98
0	1	1	0	0	0	1	1	19.5
0	1	1	0	0	1	0	0	17.26
0	1	1	0	0	1	0	1	20.21
0	1	1	0	0	1	1	0	17.98
0	1	1	0	0	1	1	1	17.51
0	1	1	0	1	0	0	0	18.98
0	1	1	0	1	0	0	1	17.27
0	1	1	0	1	0	1	0	18.53
0	1	1	0	1	0	1	1	19.86
0	1	1	0	1	1	0	0	17.86
0	1	1	0	1	1	0	1	19.18
0	1	1	0	1	1	1	0	20.06
0	1	1	0	1	1	1	1	17.29
0	1	1	1	0	0	0	0	18.41
0	1	1	1	0	0	0	1	19.26
0	1	1	1	0	0	1	0	18.48
0	1	1	1	0	0	1	1	17.29
0	1	1	1	0	1	0	0	19.32
0	1	1	1	0	1	0	1	19.92
0	1	1	1	0	1	1	0	17.15
0	1	1	1	0	1	1	1	23.01
0	1	1	1	1	0	0	0	18.6
0	1	1	1	1	0	0	1	17.05
0	1	1	1	1	0	1	0	17.38
0	1	1	1	1	0	1	1	22.02
0	1	1	1	1	1	0	0	18.82
0	1	1	1	1	1	0	1	17
0	1	1	1	1	1	1	0	17.3
0	1	1	1	1	1	1	1	19.41
1	0	0	0	0	0	0	0	18.62
1	0	0	0	0	0	0	1	19.38
1	0	0	0	0	0	1	0	16.81
1	0	0	0	0	0	1	1	19.72

1	0	0	0	0	1	0	0	17.83
1	0	0	0	0	1	0	1	20.9
1	0	0	0	0	1	1	0	16.8
1	0	0	0	0	1	1	1	17.38
1	0	0	0	1	0	0	0	18.95
1	0	0	0	1	0	0	1	19
1	0	0	0	1	0	1	0	19.62
1	0	0	0	1	0	1	1	17.96
1	0	0	0	1	1	0	0	18.76
1	0	0	0	1	1	0	1	18.54
1	0	0	0	1	1	1	0	17.36
1	0	0	0	1	1	1	1	16.93
1	0	0	1	0	0	0	0	19.14
1	0	0	1	0	0	0	1	16.54
1	0	0	1	0	0	1	0	17.64
1	0	0	1	0	0	1	1	20.92
1	0	0	1	0	1	0	0	19.16
1	0	0	1	0	1	0	1	17.68
1	0	0	1	0	1	1	0	19.34
1	0	0	1	0	1	1	1	19.68
1	0	0	1	1	0	0	0	19.14
1	0	0	1	1	0	0	1	19.36
1	0	0	1	1	0	1	0	18.09
1	0	0	1	1	0	1	1	16.58
1	0	0	1	1	1	0	0	17.03
1	0	0	1	1	1	0	1	19.18
1	0	0	1	1	1	1	0	18.41
1	0	0	1	1	1	1	1	19.02
1	0	1	0	0	0	0	0	18.3
1	0	1	0	0	0	0	1	17.45
1	0	1	0	0	0	1	0	20.09
1	0	1	0	0	0	1	1	21.4
1	0	1	0	0	1	0	0	18.72
1	0	1	0	0	1	0	1	18.21
1	0	1	0	0	1	1	0	17.33
1	0	1	0	0	1	1	1	18.46
1	0	1	0	1	0	0	0	19.23
1	0	1	0	1	0	0	1	17.37
1	0	1	0	1	0	1	0	18.68
1	0	1	0	1	0	1	1	16.56
1	0	1	0	1	1	0	0	18.86
1	0	1	0	1	1	0	1	18.3
1	0	1	0	1	1	1	0	17.87
1	0	1	0	1	1	1	1	18.92
1	0	1	1	0	0	0	0	18.15
1	0	1	1	0	0	0	1	18.29
1	0	1	1	0	0	1	0	17.76
1	0	1	1	0	0	1	1	17.31
1	0	1	1	0	1	0	0	17.16
1	0	1	1	0	1	0	1	17.24
1	0	1	1	0	1	1	0	19.54
1	0	1	1	0	1	1	1	18.27
1	0	1	1	1	0	0	0	17.89
1	0	1	1	1	0	0	1	18.07
1	0	1	1	1	0	1	0	18.88
1	0	1	1	1	0	1	1	19.27
1	0	1	1	1	1	0	0	20.06
1	0	1	1	1	1	0	1	19.02
1	0	1	1	1	1	1	0	18.17
1	0	1	1	1	1	1	1	18.31
1	1	0	0	0	0	0	0	18.38
1	1	0	0	0	0	0	1	16.95
1	1	0	0	0	0	1	0	19.24
1	1	0	0	0	0	1	1	16.5
1	1	0	0	0	1	0	0	17.7
1	1	0	0	0	1	0	1	16.57
1	1	0	0	0	1	1	0	18.99

1	1	0	0	0	1	1	1	17.15
1	1	0	0	1	0	0	0	19.48
1	1	0	0	1	0	0	1	18.41
1	1	0	0	1	0	1	0	17.93
1	1	0	0	1	0	1	1	16.9
1	1	0	0	1	1	0	0	16.72
1	1	0	0	1	1	0	1	19.07
1	1	0	0	1	1	1	0	18.32
1	1	0	0	1	1	1	1	18.47
1	1	0	1	0	0	0	0	18.03
1	1	0	1	0	0	0	1	18.53
1	1	0	1	0	0	1	0	16.92
1	1	0	1	0	0	1	1	20.59
1	1	0	1	0	1	0	0	17.87
1	1	0	1	0	1	0	1	18.47
1	1	0	1	0	1	1	0	18.5
1	1	0	1	0	1	1	1	18.74
1	1	0	1	1	0	0	0	18.22
1	1	0	1	1	0	0	1	16.98
1	1	0	1	1	0	1	0	17.95
1	1	0	1	1	0	1	1	20.23
1	1	0	1	1	1	0	0	19.11
1	1	0	1	1	1	0	1	17.78
1	1	0	1	1	1	1	0	17.02
1	1	0	1	1	1	1	1	17.14
1	1	1	0	0	0	0	0	18.53
1	1	1	0	0	0	0	1	18.21
1	1	1	0	0	0	1	0	17.91
1	1	1	0	0	0	1	1	17.07
1	1	1	0	0	1	0	0	18.06
1	1	1	0	0	1	0	1	19.44
1	1	1	0	0	1	1	0	19.12
1	1	1	0	0	1	1	1	17.92
1	1	1	0	1	0	0	0	17.9
1	1	1	0	1	0	0	1	16.56
1	1	1	0	1	0	1	0	16.99
1	1	1	0	1	0	1	1	22.67
1	1	1	0	1	1	0	0	19.66
1	1	1	0	1	1	0	1	18.84
1	1	1	0	1	1	1	0	17.49
1	1	1	0	1	1	1	1	16.94
1	1	1	1	0	0	0	0	20.1
1	1	1	1	0	0	0	1	18.47
1	1	1	1	0	0	1	0	19.06
1	1	1	1	0	0	1	1	17.48
1	1	1	1	0	1	0	0	17.27
1	1	1	1	0	1	0	1	21.79
1	1	1	1	0	1	1	0	16.83
1	1	1	1	0	1	1	1	22.46
1	1	1	1	1	0	0	0	20.4
1	1	1	1	1	0	0	1	16.69
1	1	1	1	1	0	1	0	18.13
1	1	1	1	1	0	1	1	19.69
1	1	1	1	1	1	0	0	18.6
1	1	1	1	1	1	0	1	16.6
1	1	1	1	1	1	1	0	18.84
1	1	1	1	1	1	1	1	17.9

Valve label	Valve status	Changing time	Other valves changes
1	Open Close	18.12 18.52	None
2	Open Close	17.64 16.82	None
3	Open Close	16.32 16.26	None
4	Open Close	18.08 16.56	None
5	Open Close	17.45 16.32	None
6	Open Close	17.07 19.45	None
7	Open Close	18.98 18.18	None
8	Open Close	16.27 16.03	None

Table 4.1: Direct analysis results

It is observed that only opening and closing one single valve each time, the time between changes varies within 16 and 19 seconds range approximately. Otherwise, if the combinations of valves are more extensive as shown in the exhaustive test, the slot time between valve state varies between 16 and 23 seconds.

4.2 Current calibration process

The new calibration is the result of months designing and testing hardware, software and test bench. Currently, the calibration process have been suffered some changes: summed up on the following lines:

- The maximum number of devices to be calibrated in one single calibration process has raised up to 4 devices
- The modes of operation are manual, as the previous test bench, and automatic.

With all these changes, it is may to compare the calibration time between both process. In the case of the old test bench, the calibration process has a duration of 40 minutes and the number devices calibrated is 1. On the other hand, the new test bench has a calibration process of 40 minutes (does not change because of the software core is the same) and the number of devices that can calibrated is 4.

Remembering the calculus made in section 2.2, the 13 hours and 20 minutes needed to calibrate 20 devices are turned to 3 hours and 20 minutes. Therefore, takt time has been reduced 10 hours. This time reduction affects, basically, to the costs. By reducing 10 hours everyday the time which an operator has to be paying attention to the calibration process, the costs coming from the same operator can be reduced. In this case, the reduction cost would be 200 hours approximately per month.

CHAPTER 5

BUDGET

The table 5.1 shows the cost of every component bought for this project. The components already obtained in the company, such us 24 VDC power supply, cables, tools and pipes are not included in the cost.

As it is observed on the table, it has been included the cost of Junior engineer doing the whole project, which is 900 hours assuming 8€/h.

Component	Manufacturer reference	Quantity	Unit Price (€)	Total price (€)
Control box				
Caja de ABS Fibox TA342912, TEMPO, IP65, 344x289x11.74mm	TA342912	1	43.86	43.86
Conector XLR Macho Rector 6 pines Montaje en Panel, Chapado en Plata sobre Níquel	NC6MP	8	11.35	90.8
Conector XLR Hembra Recto 6 pines Montaje de Cable, Chapado en Plata sobre Níquel	NC6FX	8	11.99	95.92
Conector XLR Hembra Recto 4 pines Montaje de Cable, Color Natural	458-008	8	3.62	28.96
Conector XLR Macho Recto 4 pines Montaje en panel, chapado en Plata sobre Níquel	NC4MDL1	8	5.34	42.76
Interruptor giratorio, 3 Posiciones, tenión máx 690Vac, corriente máxima 20A	T0-2-8230/E + EZ-P 1	8	23.10	184.8
Interruptor de palanca SPST, Funcionamiento On-Off	734-7154	8	1.83	14.64
Conector XLR Macho Recto 3 pines Montaje en Panel, Chapado en Plata, Color Natural	548-9149	2	2.99	5.98
Diodo TVS Unidireccional, 1N6277ARL4G, 1500W, Caja 41 A, 2-Pines	1N6277ARL4G	8	0.54	4.32
Diodo, 1N5401-E3, 3A, 100V, DO-201AD, 2-Pines	1N5401-E3	8	0.205	1.64
ULN2803A - Array de Transistores Bipolares, Darlington, NPN, 50 V, 2.25 W, 500 mA, 1000 hFE, DIP	ULN2803A	1	0.364	0.364
48.61.7.024.0050SPA - Relé de Propósito General, Serie 48, Interfaz, SPDT, 24 VDC, 16 A	48.61.7.024.0050SPA	8	11.89	95.12
Power supply box				
Fuente de alimentación de montaje en carril DIN, Modo conmutado, 1 salida 2.4A, 4.75V dc a 5.5V dc	712-7391	1	26.78	26.78
Transformador de carril DIN RS Pro, 24V ac, 75VA, 1 salida	805-5323	2	81.60	163.2
Filtro RFI Schurter, 1A, 250 V ac, 50 → 60Hz, Carril DIN, con terminales Tornillo, Serie FMAC RAIL	5500.2263	1	59.38	59.38
Disyuntor magnético térmico Schneider Electric GB2CD06, 1A, 1P + N, GB2	GB2CD06	1	41.16	41.16
Cuadro de distribución Spelsberg 73542801, 3 Fases, 28 vías	73542801	1	97.03	97.03
Test bench				
Actuador de válvula RS Pro, 1 puerto, 24 V, CPC3	812-5217	8	75.65	605.2
Almemo 5690-2	MAS56902M09TG3	1	2452	2452
Sensor velocidad	FVAD35TH5K1	4	635	2540
Sensor velocidad	FVAD35TH4K1	4	705	2820
Junior engineer		900 hours	8€per hour	7200
			Total	**16613.91**

Table 5.1: Budget

CHAPTER 6

FURTHER DEVELOPMENT AND CONCLUSIONS

It has been achieved the main goals defined at the beginning of the project. Basically, feedback part is only the non-assembled part because of lack of time, which it is the straightforward step to make after the end of the present project.

One other thing to do is a circuit improvement inside the control box. As it has been explained, the circuit was made on a strip board and an improvement would be to make the same circuit, but in this case by designing a PCB. Although the the time to design and to made could be large, the resulting board would be more reliable than the current one. Furthermore, the mistake error in the connection is lower if the design has been checked correctly.

As a future development also, instead of buy a box and make manually the holes, a better results would be obtained if a box was designed and manufactured by ourselves. By this way, the box appearance would be user-friendly for the operator and it would not be errors by making the holes.

On the conclusions side, the main challenge was to do a real project in a company. Despite of the project inside was not complex, all the steps to carry it out were tough. The reasons are:

- The design must be approved before to buy the components and assemble it. This approval should be made by an experienced engineer and not always it is available.
- The operators are not use to be engineers. The control box was to be designed because of an external person who does not know how the circuit works, could work with it. One of the examples was to select the components placed out of the box, such us the connectors and switches. The connectors could not be connected wrong and the switches have to be a clear function to the operator.
- The research of components. To find the suitable component for our purposes was not easy. Or the components desired were not able to find them or they were out of stock.

Personally, I think the project was satisfied for me, because I was able to use my knowledge acquired during my bachelor and master's degree and I could know how an R&D department works and, also, how a real project is developed, which I think it is useful for my future career.

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ACRONYMS

A Ampere. 8, 11, 12, 14–16, 19, 22, 27, 29, 50

CCW Counterclockwise. 9, 28, 32, 33

Coil+ Coil positive port. 11

Coil- Coil negative port. 11

COM Common. 11, 28, 32

CW Clockwise. 9, 28, 32, 33

DAC Digital Analog Converter. 33

DAQ Data Acquisition. 26, 32, 33

EMC Electromagnetic compatibility. 14

Hz Hertz. 8, 16

NC Normally Close. 11, 27, 28

NO Normally Open. 11, 27, 28

PCB Printed Circuit Board. 29, 49

pp peak to peak. 15

SPDT Simple Pole Double Throw. 12, 27

TVS Transient Voltage Suppression. 28, 29

VA Volt Ampere. 14

VAC Voltage Alternating Current. 8, 9, 11, 13–18, 21, 28, 30–32, 50

VDC Voltage Direct Current. 4, 5, 11, 13–17, 22, 24, 26–33, 47

W Watt. 8, 14, 15